12/29

TO:	ACTION	COORD	INFO
EO/ICS			X
D/ICS			X
DD/ICS			X
DD/RE			X
EA-D/ICS			X
SA-D/ICS			
SA-D/ICS-EP			
REO			
COMIREX			
SIGINT			
HUMINT			
MASINT			
IPC			
PBO			
PPO	X		
CCISCMO			
IHC			
RDCO			
LL			
SECRETARIAT			
ADMIN			
REGISTRY			

SUSPENSE: 16 Jan 89
Date

REMARKS: Respond to NSC w/ info copy to E.S.

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 RETARIAT

ROUTING SLIP

TO:

		ACTION	INFO	DATE	INITIAL
1	DCI				
2	DDCI				
3	EXDIR				
4	D/ICS	X			
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6	DDA				
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8	DDS&T				
9	Chm/NIC				
10	GC				
11	IG				
12	Compt				
13	D/OCA				
14	D/PAO				
15	D/PERS				
16	D/Ex Staff				
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SUSPENSE 16 Jan 89
Date

Remarks To # 4: Please provide your comments and clearance direct to the NSC Staff, info to ES.

Executive Secretary

STAT

28 Dec 88
Date

3637 (10-81)

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UNCLASSIFIED W/
CONFIDENTIAL ATTACHMENT

~~CONFIDENTIAL~~

~~EXEC~~ EC STAFF [redacted]

25X1

ER 88-2657X/3

~~LTA 12-SR~~

NATIONAL SECURITY COUNCIL
WASHINGTON, D.C. 20506

MEMORANDUM FOR

December 23, 1988

25X1

LTA 12-SR

MR. DONALD GREGG
Assistant to the Vice President
for National Security Affairs

[redacted]
Executive Secretary
Central Intelligence Agency

MR. MELVYN LEVITSKY
Executive Secretary
Department of State

MR. GARY L. BAUER
Assistant to the President
for Policy Development

MS. JENNIFER A. SOUR
Acting Executive Secretary
Department of Treasury

CAPTAIN ANTHONY MANESS
Executive Assistant to the Chairman
Joint Chiefs of Staff

COLONEL GEORGE P. COLE, JR.
Executive Secretary
Department of Defense

MR. ROBERTA RIFKIN
Executive Secretary
Arms Control and Disarmament Agency

MR. DONALD A. DANNER
Chief of Staff
Department of Commerce

MR. R. JOSEPH DESUTTER
Executive Director
Office of Science and Technology Policy

MS. RUTH KNOUSE
Director, Executive Secretariat
Department of Transportation

MR. HENRY E. CLEMENTS
Executive Officer
National Aeronautics and Space Administration

MR. L. WAYNE ARNY
Associate Director for National Security and International Affairs
Office of Management and Budget

MS. NANCY RISQUE
Assistant to the President
and Cabinet Secretary

SUBJECT: Space Debris Report

Reference my memorandum of June 29, 1988.

The attached report of the IG(Space) Working Group on Space Debris, produced under NSC staff-approved terms of reference, represents the consensus (with the exceptions noted) of the members of the Working Group. Those few sections of the report in which consensus has not been reached have been denoted by double brackets, and alternative formulations for these sections are included. The Working Group will continue its attempts to resolve the bracketed language, with resolution expected in early January. Final Working Group recommendations on the bracketed language will be supplied for your review as an addendum.

UNCLASSIFIED W/
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~~CONFIDENTIAL~~

Please submit your final agency comments on this report, to arrive here by January 16, 1989. The NSC staff point of contact is Roger DeKok, 395-4970.

Robert H Pento
for Paul Schott Stevens
Executive Secretary

Attachments
Tab A Working Group Report (U)
Tab B Appendix 2 (C)

TAB

A

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DEC 9 1988

TO: NSC/Roger DeKok

FROM: IG(SPACE) Working Group on Orbital Debris

SUBJECT: Report on Orbital Debris

The attached report is submitted by the IG(SPACE) Working Group on Orbital Debris and represents the consensus (with exceptions as noted) of the members of the Working Group. This document incorporates the results of the final working group review held on November 23, 1988. Those few sections of the report in which consensus has not been reached have been denoted by double brackets ([[ ]]), and alternative formulations for these sections are included in an enclosure to this cover memo.

We recommend that this report be distributed as soon as possible for full agency review prior to final adoption by IG(SPACE).

Kenneth S. Pedersen
NASA

James Binns
DoD

Enc

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-- Sections with Some Disagreement

preface

OMB prefers that a preface be inserted after the title page as follows:

> "This report is intended for internal agency and interagency planning purposes only. New programs or activities recommended in this report do not reflect Administration approval and must compete for funding in the budget process."

page 66 paragraph 4 of Regulatory Overview

DOT prefers substituting the word "regulated" for the word "reviewed."

page 69 end of Chapter 10

DOT prefers adding the following paragraph to the end of Chapter 10:

"Consistent with Federal regulatory policy as well as DOT's statutory mandate, therefore, the imposition of a requirement on the commercial launch sector to control or prevent the proliferation of space debris will be considered in a different context than governmental operations."

page 72 paragraph E of Recommendations

OMB would substitute the clause within double brackets with:

> "- within the overall resources and policy guidance provided by the President."

page 72 paragraph F of Recommendations

OMB would substitute the clause within double brackets with:

> "- within the overall resources and policy guidance provided by the President."

<u>page 73 for Recommendation "L"</u> two alternatives have been offered:

First alternate:

One year after approval of this report, the interagency working group should evaluate the progress of agency activities related to implementation of the recommendations of this report, and, on the basis of this evaluation, should propose appropriate steps designed to place the U.S. government in a position to respond efficiently and effectively to the orbital debris problem. The working group will also propose specific long-term objectives for guiding government activities and regulations for mitigating orbital debris.

Second alternate:

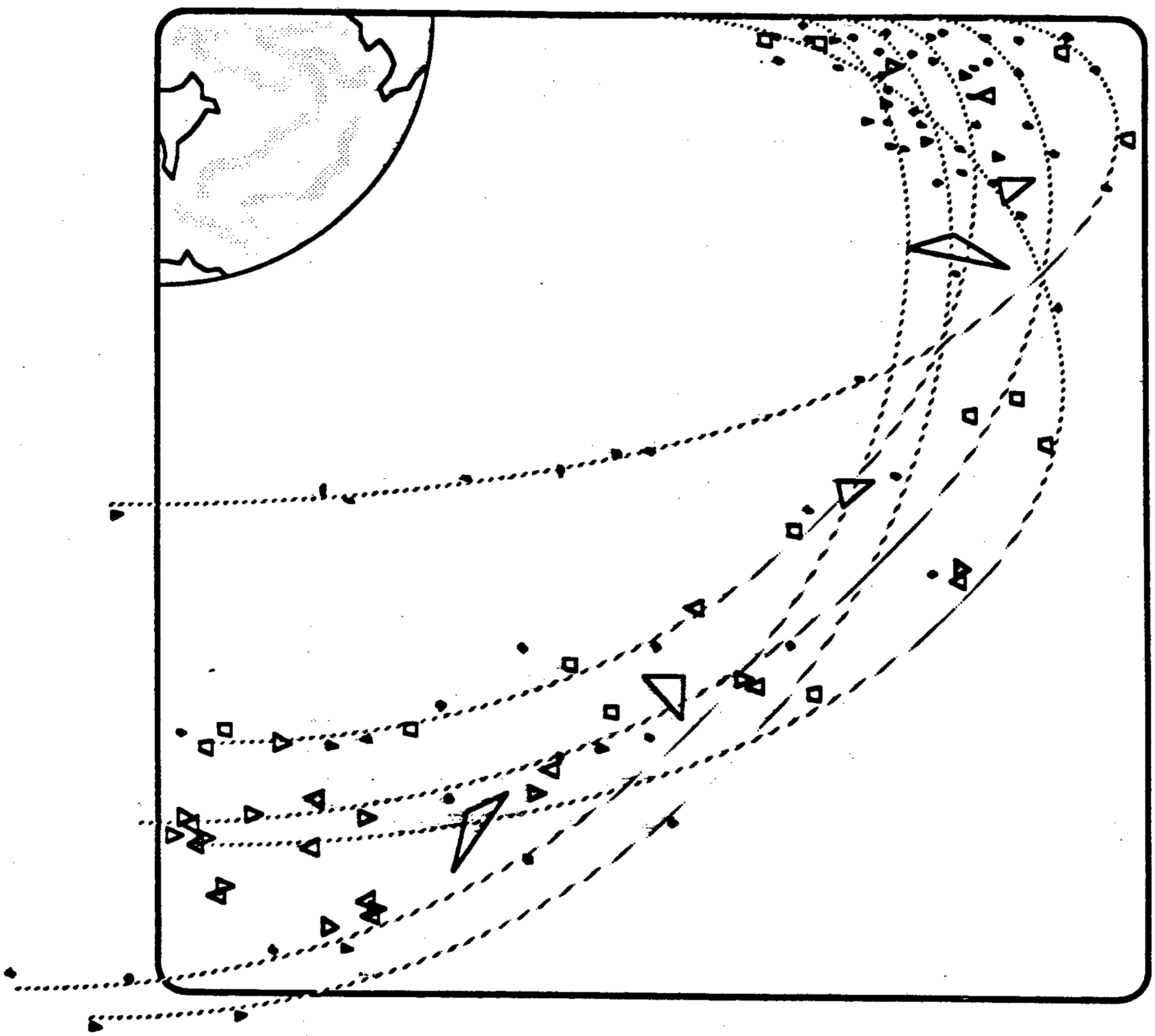
Within eighteen months from approval of this report, the interagency working group should coordinate development of a long-term strategy for researching, developing and implementing means to mitigate the accumulation of orbital debris and protect spacecraft operations (within an acceptable level of risk) from collision with debris objects. As a minimum, this strategy should include:

- establishment of long-term goals
- a provisional milestone plan and schedule leading to achievement of long-term goals
- establishment of an interagency mechanism (at the technical level) for inviting ideas, identifying promising technical and scientific innovations, evaluating concepts and coodinating research and development efforts among various agencies
- a plan for integrating regulation of the commercial industry with other debris mitigation efforts
- a plan for pursuing formal negotiations for international cooperation in debris mitigation efforts
- a plan for evaluating progress in the mitigation of the orbital debris problem
- a plan for monitoring compliance with national and agency policies/regulations
- projected funding needs

WORKING GROUP REPORT ON ORBITAL DEBRIS

IG-Space Working Group For Orbital Debris

December 7, 1988



Prepared For:

National Security Council
Washington, D.C.

WORKING GROUP REPORT ON ORBITAL DEBRIS

for

INTERAGENCY GROUP(SPACE)

by

IG-SPACE WORKING GROUP FOR ORBITAL DEBRIS

DECEMBER 7, 1988

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FINAL DRAFT REPORT ON ORBITAL DEBRIS for IG (SPACE)

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GLOSSARY

ASAT - Anti-Satellite
CCD - Charge Coupled Device (or Detector)
COLA - Collision Avoidance on Launch
COMBO - Computation of Miss Between Orbits
DECR - Debris Environment Characterization Radar
DOC - Department of Commerce
DoD - Department of Defense
DOT - Department of Transportation
ELV - Expendable Launch Vehicle
EVA - Extravehicular Activities
FCC - Federal Communications Commission
FMEA - Failure Modes and Effects Analysis
GEO - Geosynchronous Earth Orbit
GLONASS - Global Navigation Satellite System (USSR)
GOES - Geostationary Operational Environmental Satellite
GPS - Global Positioning System
GTO - Geosynchronous Transfer Orbit
ITU - International Telecommunications Union
JPL - Jet Propulsion Laboratory
LEO - Low Earth Orbit
LRIR - Long Range Imaging Radar
MEO - Medium Earth Orbit
MIT - Massachusetts Institute of Technology
NASA - National Aeronautics and Space Administration
NOAA - National Oceanic and Atmospheric Administration
SPADOC - Space Defense Operations Center
SSN - Space Surveillance Network
UCT - Uncorrelated Target
UCTP - Uncorrelated Target Processor

PART ONE: DIMENSIONS OF THE ORBITAL DEBRIS PROBLEM

INTRODUCTION

The natural meteoroid environment has historically been a design consideration for spacecraft. Meteoroids are part of the interplanetary environment and sweep through earth orbital space at an average speed of 20 km/sec. Observational data indicate that, at any one time, a total of about 200 kg of meteoroid mass is within 2000 km of the earth's surface, the region containing the most-used orbits. Most of this mass is in meteoroids about 0.01 cm diameter; lesser amounts of this mass are found in sizes both smaller and larger than 0.01 cm. This natural meteoroid flux varies in time as the earth revolves about the sun.

Man-made space debris (referred to as "orbital debris" throughout the rest of this document) differs from natural meteoroids because it remains in earth orbit during its lifetime and is not transient through the space around the earth. This study only considers the orbital debris environment and not reentering debris.

The estimated mass of man-made orbiting objects within 2000 km of the earth's surface is about 3,000,000 kg (15,000 times more than the meteoroid mass). These objects are in mostly high inclination orbits and pass one another at an average relative velocity of 10 km/sec (about 22,000 mph). Most of this mass is contained in about 3000 spent rocket stages, inactive satellites, and a comparatively few active satellites. A smaller amount of mass, about 40,000 kg, is in the remaining 4000 objects currently being tracked by space surveillance sensors.

Most of these objects are the result of over 130 on-orbit fragmentations (see Appendix 1 for a detailed list). Recent ground telescope measurements of orbital debris combined with analysis of hypervelocity impact pits (from man-made debris) on the returned surfaces of the Solar Max satellite indicate a total mass of about 1000 kg for orbital debris sizes of 1 cm or smaller, and about 300 kg for orbital debris smaller than .1 cm. This distribution of mass and relative velocity is sufficient to cause the orbital debris environment to be more hazardous than the meteoroid environment to most spacecraft operating in earth orbit below 2000 km altitude.

Information about the current debris environment is extremely limited by the inability to effectively track objects smaller than 10 cm in diameter. The current Space Surveillance Network was not designed to track small particles (less than 10 cm) debris as part of its mission. Furthermore, technological, natural and fiscal constraints limit the alternative for modifying existing sensors or adding new systems.

CHAPTER 1: THE CURRENT ENVIRONMENT

I. DESCRIPTION OF THE SPACE ENVIRONMENT

A. Background

Two types of orbital debris are of concern:

(1) Large objects (greater than 10 cm in diameter) whose population, while small in absolute terms, is large relative to the population of similar masses in the natural debris environment; and

(2) A much greater number of smaller objects (less than 10 cm diameter), whose size distribution approximates natural meteoroids and which add to the natural debris environment in those size ranges.

The interaction of these two classes of objects, combined with their long residual times in orbit, leads to further concern that inevitably there will be collisions producing additional fragments and causing the total debris population to grow.

The space around the earth is generally divided into three orbital regimes:

(1) Low Earth Orbit (LEO) - defined by objects orbiting the earth at less than 5500 km altitude; this equates to orbital periods of less than 225 minutes.

(2) Medium Earth Orbit (MEO) - defined by objects orbiting the earth between LEO and GEO altitudes.

(3) Geosynchronous Earth Orbit (GEO) - defined by objects orbiting the earth at an altitude of approximately 35,863 km; this equates to an orbital period of approximately 24 hours.

Objects orbit the earth in two basic types of orbits:

(1) Circular - the object remains at a constant distance from the center of the earth for its entire orbit. The object's velocity remains constant throughout each revolution of the earth. Circular orbits are special cases of the more general elliptical orbits and only "approximate" true circles.

(2) Elliptical - the object's distance from the center of the earth varies as it follows the shape of an ellipse during each revolution. The closest point of approach to the earth is called the object's perigee;

the farthest point from the earth is called the object's apogee. Objects achieve maximum velocity at perigee and achieve minimum velocity at apogee.

The greatest number of tracked objects are in LEO, the next greatest are in GEO, and the remaining objects are in MEO. Two new navigation systems (the U.S. Global Positioning System (GPS) and U.S.S.R. Global Navigation Satellite System (GLONASS) satellite constellations) are the first major users of MEO.

A typical altitude distribution of objects tracked (limited by sensor capability to objects greater than 10 cm in diameter) in LEO up to 2000 km is shown in Figure 1, where the average number of objects at any one time is found in a 10 km altitude band is plotted against altitude. The peak density is near 800 km, where the density is about 200 objects in a 10 km altitude band. At 350 to 500 km altitudes, where the International Space Station (hereinafter called Space Station) would operate, the density is about 20 to 50 objects in a 10 km altitude band.

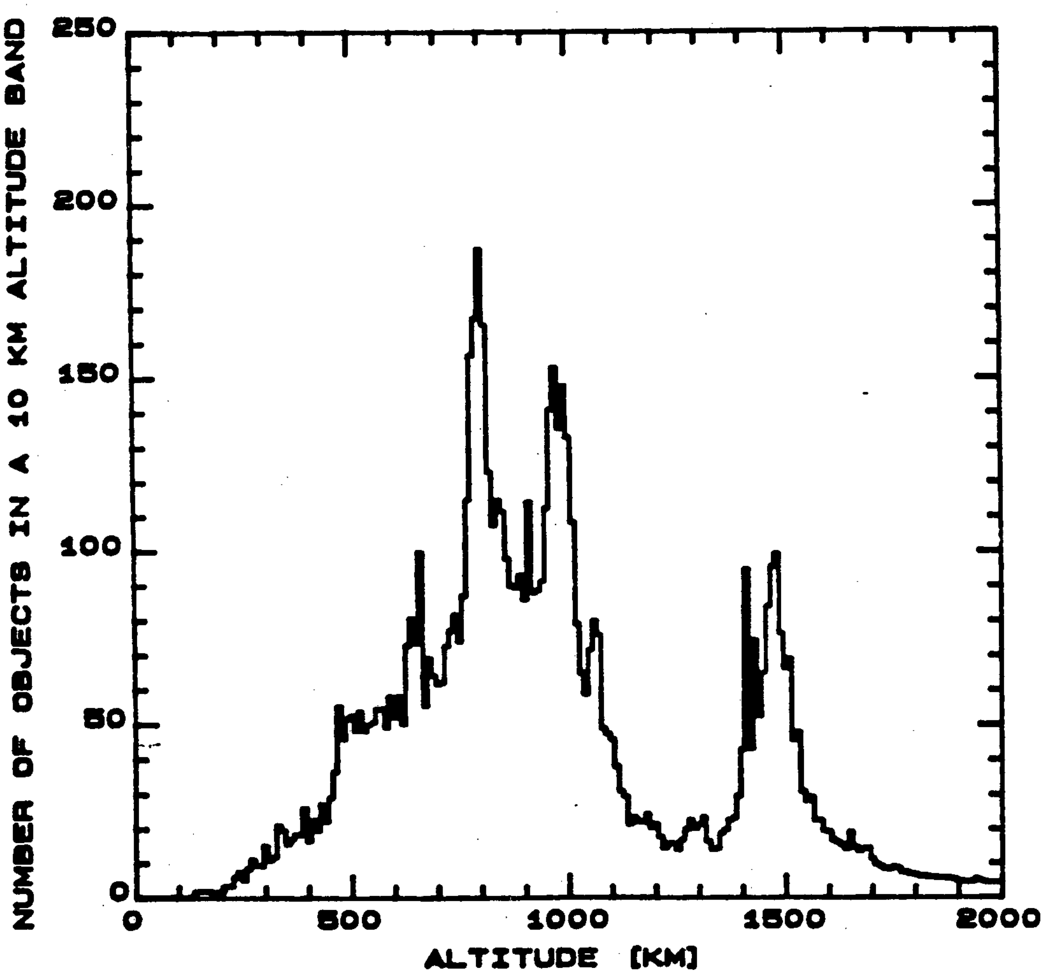


Figure 1: Altitude Distribution of Objects in Low Earth Orbit

Figure 2 shows a "snapshot" of objects tracked in GEO by their longitude. The objects along the 0 degree latitude (equator) band are in geostationary orbit. The other objects, for the most part, have a slightly inclined orbit which causes them to trace a figure-eight pattern on the ground about a point on the equator, completing the pattern once every 24 hours.

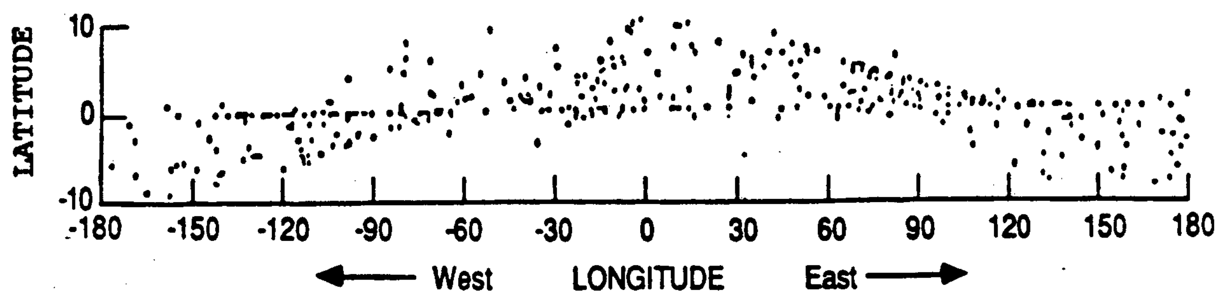


Figure 2: Distribution of Objects in Geosynchronous Earth Orbit

B. Debris Distribution

U.S. Space Command presently maintains a catalog of more than 7000 objects in space. The majority of these cataloged objects are in low earth orbit and are 10 cm in diameter or larger due to tracking limitations. As the altitude increases the minimum sized detectable objects increases due to sensor limitations. The breakdown of the tracked objects, indicated by Table 1, reveals the relative distribution of the objects by altitude as of August 1, 1988.

TABLE 1: TRACKED OBJECTS BY ALTITUDE

ORBIT TYPE	LEO	MEO	GEO	TOTAL
TOTAL TRACKED OBJECTS	5923	683	453	7059

Extrapolation from the tracked objects, examination of various objects returned to earth, and radar and optical debris observations result in predictions that the 7000 tracked objects represent only about 0.2% of the orbital debris population. Table 2 shows the estimated debris population from both a numeric and mass on orbit perspective.

TABLE 2: ESTIMATED DEBRIS POPULATION

<table>
<tr><th>Size</th><th>No. Objects</th><th>% by No.</th><th>Mass on Orbit</th><th>% by Mass</th></tr>
<tr><td>>10 cm</td><td>7,000</td><td>0.2%</td><td>2,999,000 kg</td><td>99.97%</td></tr>
<tr><td>1-10 cm</td><td>17,500</td><td>0.5%</td><td rowspan="2">1,000 kg</td><td rowspan="2">0.03%</td></tr>
<tr><td><0.1-1 cm</td><td>3,500,000</td><td>99.3%</td></tr>
<tr><td>Total</td><td>3,524,500</td><td>100 %</td><td>3,000,000 kg</td><td>100 %</td></tr>
</table>

Small debris is normally defined as objects smaller than 10 cm in diameter. Computer simulations predict approximately 17,500 objects 1 - 10 cm in diameter (about 0.5% of the total population) and 3,500,000 objects between 0.1 and 1 cm (99.3%). However, observations from optical telescopes and analysis of material retrieved from orbit are the only current empirical data sources. Data derived from these ground-based and in-space measurements reveal an increasing debris population with decreasing debris piece size. Explosions of large objects have the potential of producing a much larger number of smaller objects, objects too small to be detected by current space surveillance sensors. This is especially true in high-intensity explosions, or in explosions where the payload is designed to break up into some particular size. It is theoretically possible for a single 100 kg payload to break up into 10^5 1 cm objects or into 10^8 0.1 cm objects. A break-up due to a typical hypervelocity collision involving a 100 kg payload would probably create somewhat fewer objects, on the order of 10^4 1 cm objects or 10^6 0.1 cm objects. Low-intensity explosions could produce on the order of 10^3 objects of either size. These estimates are based on extrapolations from experimental data.

C. Orbital Lifetime

An orbiting object loses energy through friction with the upper reaches of the atmosphere and various other orbit perturbing forces. Over time the object falls into progressively lower orbits and eventually falls to the earth. As the object's potential energy (represented by its altitude) is converted to kinetic energy (energy due to its velocity), orbital velocity must increase as the altitude decreases. As an object's orbital trajectory draws closer to earth, it speeds up and outpaces objects in higher orbits. In short, a satellite's orbital altitude decreases gradually while its orbital speed increases. Once an object enters the measurable atmosphere, atmospheric drag will slow it down rapidly and cause it to either burn up or deorbit and fall to earth.

In LEO, unless reboosted, satellites in circular orbits at altitudes of 200-400 km reenter the atmosphere within a few months. At 400-900 km orbital altitudes, orbital lifetimes can exceed a year or more depending upon the mass and area of the satellite. For example, a glass marble in a circular orbit at 500 km will stay aloft for about a year, but if it were in orbit at 800 km it would stay up for 30 years. Above about 900 km altitudes, orbital lifetimes can be 500 years or more. Satellite earth orbit lifetimes are a function of drag and ballistic coefficients. The more mass per unit area of the object, the greater the ballistic coefficient and the less the object will react to atmospheric drag. For example, a fragment with a large area and low mass (e.g., aluminum foil) has a low ballistic coefficient and will decay much faster (and hence a shorter orbital life) than a fragment with a small area and a high mass (e.g., a ball bearing). The combination of a variable atmosphere and unknown ballistic coefficients of space objects make decay and reentry prediction difficult and inexact.

Orbital lifetimes for objects in elliptical orbits can vary significantly from lifetimes of objects in circular orbits. For elliptical orbits, the lower the perigee altitude, the greater the atmospheric drag effects. Therefore, considering a circular and an elliptical orbit with equal energies, an object in an elliptical orbit will have a higher apogee decay rate and a shorter on-orbit lifetime.

The natural decay of earth-orbiting debris is also greatly affected by the eleven year solar cycle. The last solar cycle peaked in 1981 and was above average in solar activity. The next solar cycle, expected to peak in approximately 1990, is also predicted to have significant impact on the natural decay rates. High solar activity heats the earth's upper atmosphere, which then expands and moves to higher altitudes. With this heating, the upper atmosphere density increases, causing satellites and debris to decay more rapidly. As a result, the debris population changes with solar activity depending on altitude. Above 600 km, the atmospheric density is already so low that the change in density does not noticeably affect the debris population, but below 600 km there are very noticeable changes. Over the course of the solar sun spot average eleven year cycle, the earth's atmosphere is excited and rises significantly above its median altitude. However, this natural process of "cleansing" (during the entire solar cycle) is extremely slow and alone cannot offset the present rate of debris generation.

D. Debris Effects

The effects of orbital debris impacts depend on velocity and mass of the debris. For debris of sizes less than about 0.01 cm, surface pitting and erosion are the primary effects. Over a long period of time, the cumulative effect of individual particles colliding with a satellite might become significant since the number of particles in this size range is very large in LEO.

For debris larger than about 0.1 cm, structural damage to the satellite becomes an important consideration. For example, a 0.3 cm sphere of aluminum traveling at 10 km/sec has about the same kinetic energy as a bowling ball traveling at 100 kilometers per hour (60 mph). It is reasonable to expect significant structural damage to the satellite if such an impact occurs.

It is currently practical to shield against debris particles up to 1 cm in diameter, a mass of 1.46 grams or 0.05 ounces. For larger sizes of debris, current shielding concepts become impractical. Advanced shielding concepts may make shielding against particles up to 2 cm diameter reasonable but it is possible that the only useful alternative strategy for large particles will be avoidance. Fortunately, for average size spacecraft the number of particles larger than 10 cm is still small enough that a collision with them is unlikely. For very large spacecraft, collision probabilities are sufficiently high that an alternate means of protection may be required.

For spacecraft design, it is useful to distinguish three debris size ranges:

- Sizes 0.01 cm and below produce surface erosion.
- Sizes 0.01 cm - 1 cm produce significant impact damage which can be serious, depending upon defensive design provisions.
- Objects larger than 1 cm can produce catastrophic damage.

Figure 3 shows the effects of representative sizes of debris.

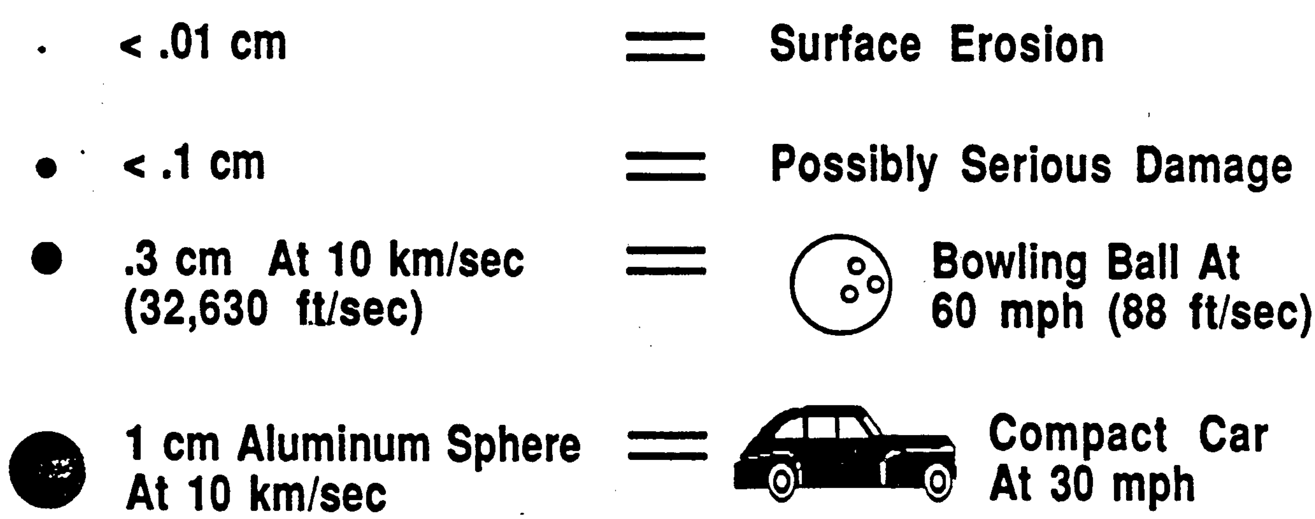


Figure 3: Kinetic Energy and Debris Effects Comparisons for Collisions at 10 km/sec

Since debris damage is a function of relative velocity and velocities at geosynchronous altitudes are low, the danger of impact is small and the possible consequences are of less immediate concern than in LEO. MEO, as one would expect, is an intermediate case.

E. Uncertainty in the Orbital Debris Environment

There is a high degree of uncertainty in our knowledge of the current orbital debris environment and in our projections of the future environment. Factors which contribute significantly to this uncertainty are (1) limited measurements, (2) a lack of predictability in the level of future space activities, and (3) the indeterminate causes of breakup events as major debris sources.

It is generally accepted that the low earth orbit environment has been measured adequately by space surveillance sensors for orbital debris sizes larger than 10 cm, and these data provide a basic estimate of the orbital debris population. Mathematical models of spacecraft or rocket body breakups are used to predict the sizes and number of fragments smaller than 10 cm. These predictions are then compared with limited telescope and special radar observations. The difference between the expected number of objects to be detected and the number actually observed becomes an estimate of the uncertainty of the populations. Based upon these data, the population density of the measured debris is known to an uncertainty factor of two to five, depending upon the diameter of the debris. However, for debris 0.1 - 1 cm, there are no confirmed measurements, and the estimates given here are based on a linear extrapolation which has an uncertainty factor of 10.

II. SOURCES OF ORBITAL DEBRIS

A. General

Both the U.S. and the U.S.S.R. share roughly equal responsibility for the current orbital debris environment, although the rate of growth in Soviet-related debris seems to be increasing, as shown in Figure 4. The figure depicts the dramatic growth of the cataloged satellite population between important milestones of the space age despite a global launch rate which has remained fairly constant for more than twenty years. Only during 1978-1981 did the catalog growth rate decline. This phenomenon was not the work of man but of the elevation of the atmosphere by a strong solar maximum. This significantly accelerated the decay of satellites and debris in orbits below about 600 km.

Satellite fragmentations (see para. II.B.) are the primary source for the recent climb in the Soviet debris population; likewise, the single breakup of a French Ariane rocket body in 1986 is responsible for the large increase in debris from other spacefaring nations and organizations.

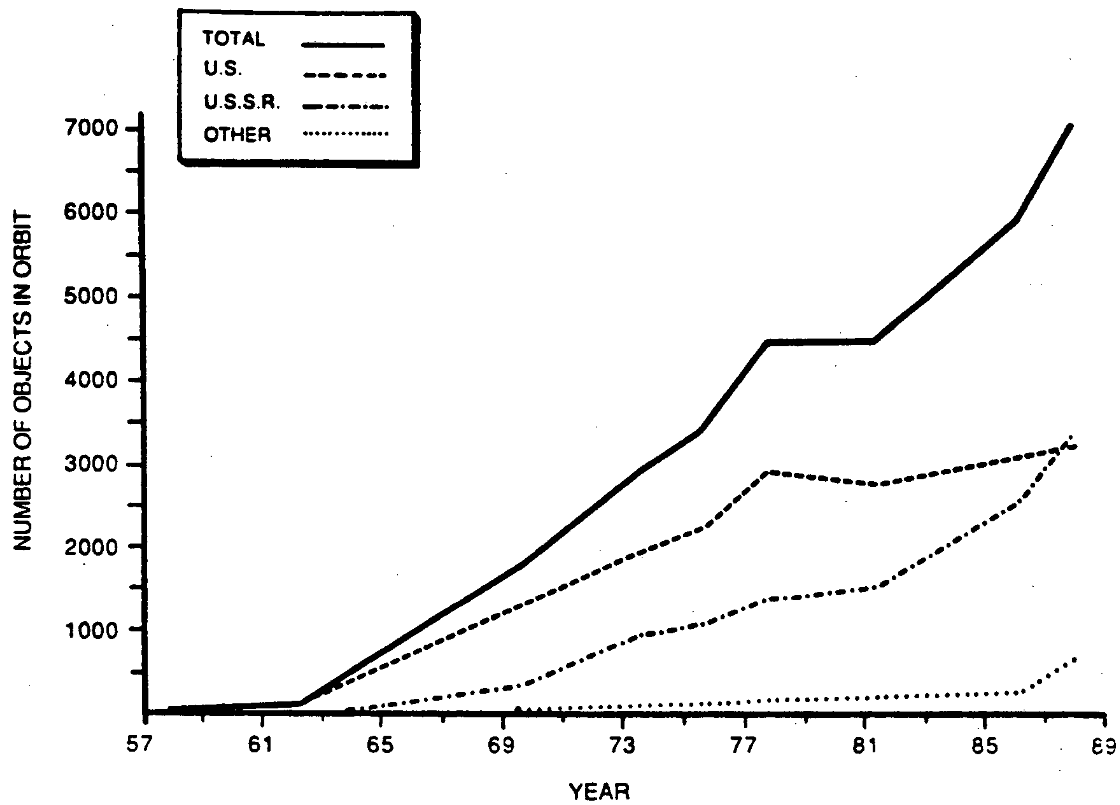


Figure 4: Number of Cataloged Space Objects In Orbit

Only 5% of the cataloged objects in earth orbit represent operational spacecraft. The remainder constitute varying types of orbital debris in four general categories:

- Operational debris (12%) - objects intentionally discarded during satellite delivery or satellite operations, including lens caps, separation and packing devices, spin-up mechanisms, empty propellant tanks, payload shrouds, or a few objects thrown away or dropped during manned activities.

- Spent and intact rocket bodies (14%)

- Inactive (dead) payloads (20%)

- Fragmentation (49%)

Thus, 95% of the cataloged objects in earth orbit can be considered orbital debris; 100% of the objects are potential sources for more debris should further breakup occur.

Table 3 presents the altitude distribution of the sources of tracked objects discussed above. As shown by the table, the majority of tracked objects are in LEO. This is an indication both of the capabilities of the tracking sensors and of the level of space activity in LEO.

TABLE 3: <u>SOURCES OF TRACKED OBJECTS BY ALTITUDE</u>

	ACTIVE/INACTIVE SPACECRAFT	ROCKET BODIES	FRAGMENTARY & OTHER	TOTAL DEBRIS
LEO	1134	651	4138	5923
MEO	232	302	149	683
GEO	329	123	1	453
TOTAL	1695	1076	4288	7059*

* 472 tracked objects pending entry in the catalog

In addition to launches, operations and fragmentations, satellite deteriorations (the decomposition of thermal blankets and the cracking and peeling of spacecraft paints) are a potentially significant source of small size orbital debris. However, such debris are not in the satellite catalog since they are undetectable due to their very small size and poor reflectivity.

B. <u>Fragmentation</u>

Since the first recognized fragmentation in June, 1961, over 130 objects (payloads, rocket bodies, and other debris) have experienced on-orbit breakups. On-orbit fragmentations may result from explosions or collisions, and may be intentional or accidental. An object may be deliberately destroyed by an explosive charge as part of a spacecraft test, or a rocket stage may suffer a catastrophic propulsion failure leading to an explosion. Collisions are less common, with a few candidate cases still being investigated. The major contributor to the increase in orbital debris in recent years has been the U.S.S.R.'s deliberate destruction of military satellites which have malfunctioned, perhaps in an effort to keep them from falling into unfriendly hands. The causes of many fragmentations (45%) remain unknown, in part due to the limited data available for analysis. Table 4 lists the causes of fragmentations as currently known.

TABLE 4: CAUSES OF SATELLITE FRAGMENTATIONS

Cause	Percent Events	Per Cent of Total Fragmentation Debris
Unknown	45	37
Deliberate	40	36
Propulsion Related	15	27

Of particular concern is the sustained and, indeed increasing, rate of fragmentation events. Whereas this trend was mitigated in the first part of the 1980s by a decrease in the observed number of debris per event, today we are witnessing a high rate of myriad multi-particle fragmentations (see Appendix 1 and Figure 5).

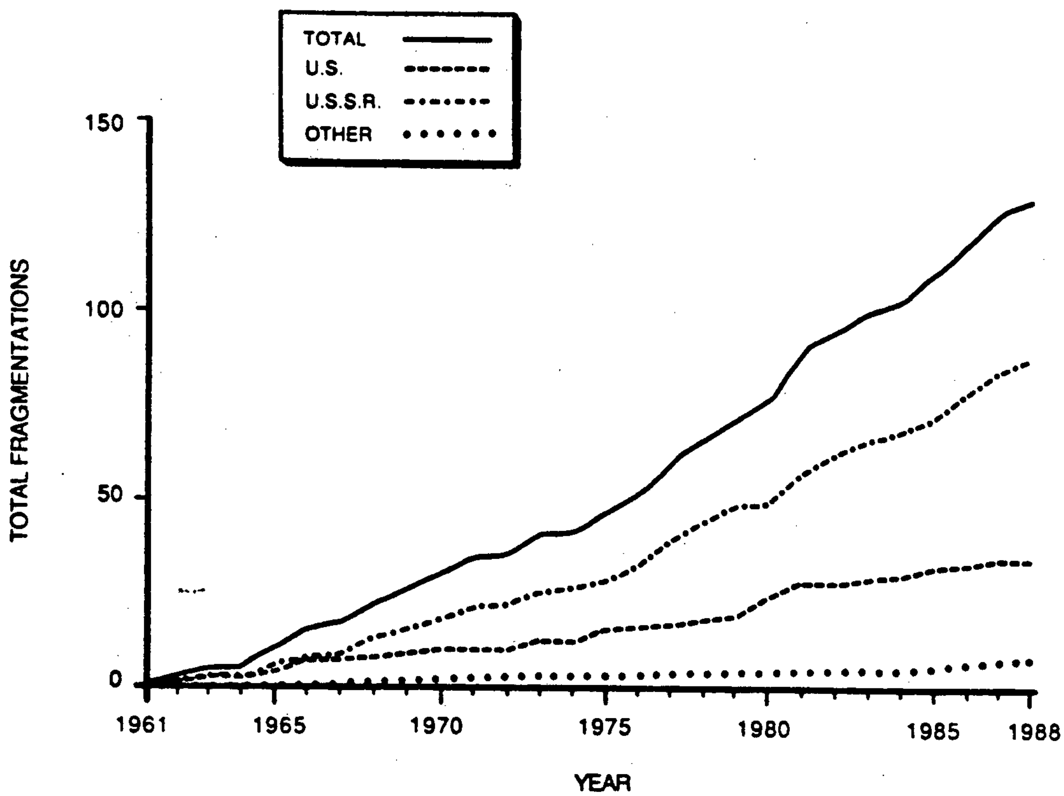
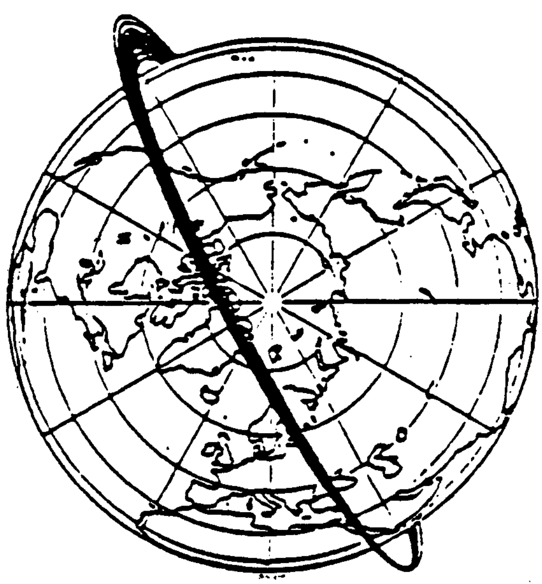


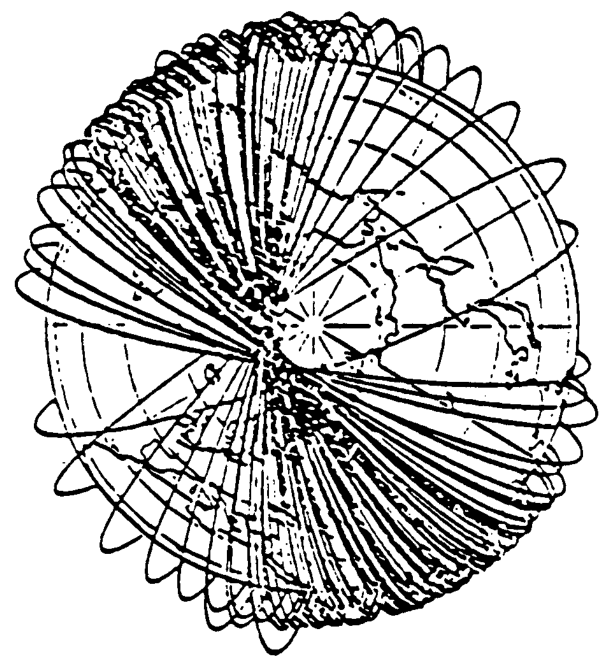
Figure 5: History of Fragmentation Events

Between June 1, 1987 and June 1, 1988, ten satellite breakups occurred of which 7 involved payloads, 2 were rocket bodies, and 1 was a satellite shroud. The national origins of the objects were eight U.S.S.R., one U.S., and one E.S.A. Particularly disturbing is the increase of large fragmentations in the lower altitude regimes traveled by manned spacecraft. This increase represents a potential threat to the safety of manned operations in space.

The Ariane Spot 1 rocket body represents the single greatest source of debris now in orbit about the earth. Figure 6 shows the orbital planes of the debris immediately after explosion and one year after the breakup. Each line indicates only the orbital track of a single small fragment not a solid band of debris. Right after a fragmentation, the debris quickly forms a ring within a narrow band of orbital planes constrained by the changes in inclination, normally a degree or less. The orbits are also constrained in altitude by changes in the perigee and apogee, normally several hundred kilometers. However, the orbital planes begin to spread apart. The rate of this separation is a function of inclination and mean altitude of the debris. Eventually, debris cloud dispersion has advanced to such an extent that the tracks of the orbiting debris trace a thin shell about the earth with a hole centered at each pole.



IMMEDIATELY AFTER EXPLOSION



1 YEAR AFTER EXPLOSION

Figure 6: Dispersion of Debris Fragments of Nov 1986 breakup of Ariane flight 16 upper stage. Each line indicates only the orbital track of a single small fragment - not a solid band of debris.

The rate of debris-producing collisions varies as the square of the number of objects in space. If it is assumed that the number of objects is proportional to the amount of mass in orbit, (a conservative assumption) then a doubling of the amount of mass in orbit would lead to a factor of four increase in the rate of debris-producing collisions.

Collisions between objects in LEO are expected to occur at an average velocity of 10 km/sec. At such velocities, the impact shock wave creates such temperatures and pressures internal to the materials to cause them to melt and millions of particles to be created. Because of this phenomenon, a hypervelocity (approximately 5-10 km/sec) collision produces many more minute particles than a chemical explosion or a pressure rupture.

Based on the current and projected growth of debris population density, there is a greater than 50% probability that one or more such catastrophic collisions will occur between trackable debris objects by the year 2000.

If explosions have occurred in GEO, few fragments would have been detected due to sensor limitations. Also, non-operational satellites in GEO are frequently not tracked for long periods of time during which unobserved fragmentations could occur. Currently, we are able to catalog only objects larger than 30 cm, and most likely 1 m, in GEO. In the absence of data to the contrary, it is believed that there is not a significant number of objects in GEO to cause a problem at this time, but increasing numbers may create a problem in the future.

C. <u>Satellite Deterioration and Solid Propellant Particles</u>

Very small orbital debris particles (sizes less than 0.05 cm) are created by disintegration of spacecraft surfaces (paint flaking, plastic and metal erosion) and by the firing of solid propellant motors, which produce aluminum oxide particles. Thousands of pounds of aluminum oxide dust are introduced each year to the space environment as a result of solid rockets fired to transfer payloads from LEO to GEO. A single rocket can be responsible for placing billions of particles in space (2,000 to 12,000 kg of aluminum oxide). Since the transfer orbits are elliptical orbits, most of the particles reenter quickly because of the effects of atmospheric drag and other forces at the orbit perigee. But the small fraction of particles that remains in orbit is still of concern. Due to the large number of particles ejected by each motor, these aluminum oxide particles can represent a significant surface erosion and contamination threat to spacecraft.

The disintegration of spacecraft exterior paints believed to be caused by atomic oxygen erosion of the organic binder of the paint is another major source of small debris in LEO. Stage and spacecraft separation processes that occur in orbit also frequently release small debris.

D. Uncertainties

Although the consequences of every satellite breakup are unique, even for identical satellites, some general trends can be stated based on observations and modeling. Statistically, rocket body fragmentations create an average of 125 trackable pieces of debris per event while a payload fragmentation creates an average of only 50 trackable pieces. There is considerable uncertainty in these figures, however, since the official satellite catalog may not include debris in very low LEO that reenters relatively quickly nor debris in GEO (if GEO breakups have indeed occurred) that may be untrackable due to sensor limitations.

CHAPTER 2: TRENDS AND IMPLICATIONS

I. TRENDS

A. Launch Activity

Space activity is placing debris in orbit faster than the natural effects of drag removes it, with the result that the tracked population of orbital debris is increasing by about 300 objects per year during a time when launch rates are fairly constant. This rate of increase includes only debris having sizes of 10 cm or larger. The increase in number of smaller objects may be much larger.

For the first 25 years of man's involvement in space, only the U.S. and the U.S.S.R. launched significant numbers of spacecraft. Currently, six countries and Arianespace, the European launch corporation, are capable of launching objects into earth orbit. Launch rates for the last nine years are illustrated in Table 5.

TABLE 5: LAUNCH OPERATIONS

Country or Organization	Number of Successful Launches in Given Year								
	1980	1981	1982	1983	1984	1985	1986	1987	1988*
U.S.S.R.	89	98	101	98	97	97	91	93	70
United States	12	18	18	22	21	17	6	9	10
Japan	2	3	1	3	3	2	2	3	2
India	1	1	0	1	0	0	0	0	0
China	0	1	1	1	3	1	2	2	3
Arianespace	0	2	0	2	4	3	2	2	5
Israel	0	0	0	0	0	0	0	0	1*
Totals	104	123	121	127	128	120	103	109	91*

* as of 9/29/88

B. Debris Modeling

In order to project the future debris environment, assumptions have to be made concerning debris sources and solar activity. With regard to debris sources, assumptions have to be made concerning launch and fragmentation rates. Random collision fragmentation is tied to the assumptions made about the launch rates. Uncertainties derive from observational limitations, unmodeled sources, and unpredictable solar activity.

The currently used NASA debris model makes the following baseline assumptions:

(1) The rate of growth of the trackable debris population has fluctuated over the years with the solar cycle, launch activity, and operational practices. The model assumes that no further preventative measures will take place, and that operational practices will not change. The launch rate used by the model is generated by combining three traffic models: a NASA model called the Civil Needs Data Base (CNDB) which includes U.S. civil government and commercial missions; a DoD model for national defense related missions; and a contractor-developed model for foreign government and commercial missions. This combined traffic model projects constrained (low), nominal (medium), and high levels of space launch activity.* Projected space launch activity includes planned SDI testing, but makes no assumptions about deployment of space-based ballistic missile defense systems. Such deployment would produce some increase in launch activity. Development of technologies to cause spent boosters and payloads to reenter might eliminate or substantially reduce the deployment phase increase of mass in orbit.

(2) The population of small untracked debris is expected to increase at an even faster rate than the tracked debris. This is because, as the population of tracked debris grows, collisions will begin to occur with increasing frequency. Hypervelocity collisions

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* The Civil Needs Data Base (CNDB), version 1.1 was utilized in estimating U.S. civil/U.S.-launched foreign traffic; Option I (the Core program), II (the Baseline program), and IV (Aggressive expansion) are represented in the Constrained, Nominal, and High traffic model, respectively. Department of Defense (DoD) Constrained models are used for the Constrained traffic model, whereas the DoD nominal growth model appears in Nominal and High traffic models. (<u>DoD Space Transportation Mission Requirements Definition</u>, Aerospace Report TOR-0086A (2460-01)-1, Volume 1, December 1986, updated Dec 87.) Rocket bodies and associated upper stages are not manifested in either of these data bases and thus their dry masses are not included in the mass totals. Also, servicing or retrieval missions, which leave no mass in orbit, and such expendable payloads as fuel, are excluded from the tally. Estimates of long-lived foreign mass are derived from Johnson's <u>History and Projections of Foreign Satellite Mass to Earth Orbit</u> (Teledyne Brown Engineering CS86-USASDC-0015, July 1986.) The dry masses of rocket bodies and upper stages are included in these mass totals. Since these projections for foreign traffic extend to the year 2000 only, foreign mass deposition is assumed constant after the year 2000.

generate very large numbers of small debris particles. As a consequence, it is reasonable to suppose that the untracked debris population will increase at about double the rate of growth of the trackable population.

(3) After the next peak in the solar cycle (circa 1990), it is assumed that solar activity peaks will be of average intensity.

Future small debris may originate primarily from random collisions between orbiting objects. Because of the possibility of cascading collisions (collisions created by previous collisions), the small debris may increase at a much faster rate than can be predicted by using the launch rate alone.

C. <u>Debris Generation Projections</u>

The major source of both large and small debris in LEO has been fragmentation of satellites and rocket bodies. This process has produced more large, trackable debris than has space operations, and very much more small untrackable debris. The launching of a payload into space from a booster or upper stage generates orbital debris composed of spent rocket stages, clamps, shrouds, covers, etc., but does not produce much untrackable debris (sizes smaller than 10 cm) in LEO.

If our current launch procedures continue, along with a high rate of fragmentation events, and launch rates increase, then debris generation rates will certainly increase. Figure 7 illustrates the past accumulation of mass in LEO (using U.S. Space Command data) and shows the projected accumulation using the traffic models described above. These traffic models predict an increasing debris growth rate such that, unless efforts are taken to moderate debris generation, an accumulation of between 8.5 million kg and 12.2 million kg in LEO will be reached by the year 2010.

The rate that the population of small uncataloged debris increases is a very sensitive function of the accumulation rate of mass in orbit and the effectiveness of efforts to moderate debris generation. For example, the NASA orbital debris model predicts that, if future launch activity follows the constrained traffic model, and efforts are taken to moderate debris (e.g. eliminating future on-orbit explosions and planning the reentering of upper stages), then a "stable" orbital debris environment might ensue. That is, even though the uncataloged population will increase with time, it would someday, perhaps a century from now, reach a "steady-state" condition where small debris is removed at the same rate at which it is generated. While this steady-state condition may require more protection for spacecraft than is required today, it would not be so severe as to preclude operations.

On the other hand, if future launch activity follows the nominal traffic model (ie. continues to escalate past the year 2010), and if no further efforts are taken to moderate debris, then an unstable environment may eventually ensue. That is, a critical density of objects could be reached, causing a very rapid, runaway increase in the debris population. During such a stage, the number of objects in orbit could be so large that random collisions occur at shorter and shorter intervals as each event creates particles which then can collide with other particles. The operational environment would then become highly unstable. Although such a condition would not prohibit launching vehicles, some altitude bands and inclinations would become too hazardous for operation of future spacecraft.

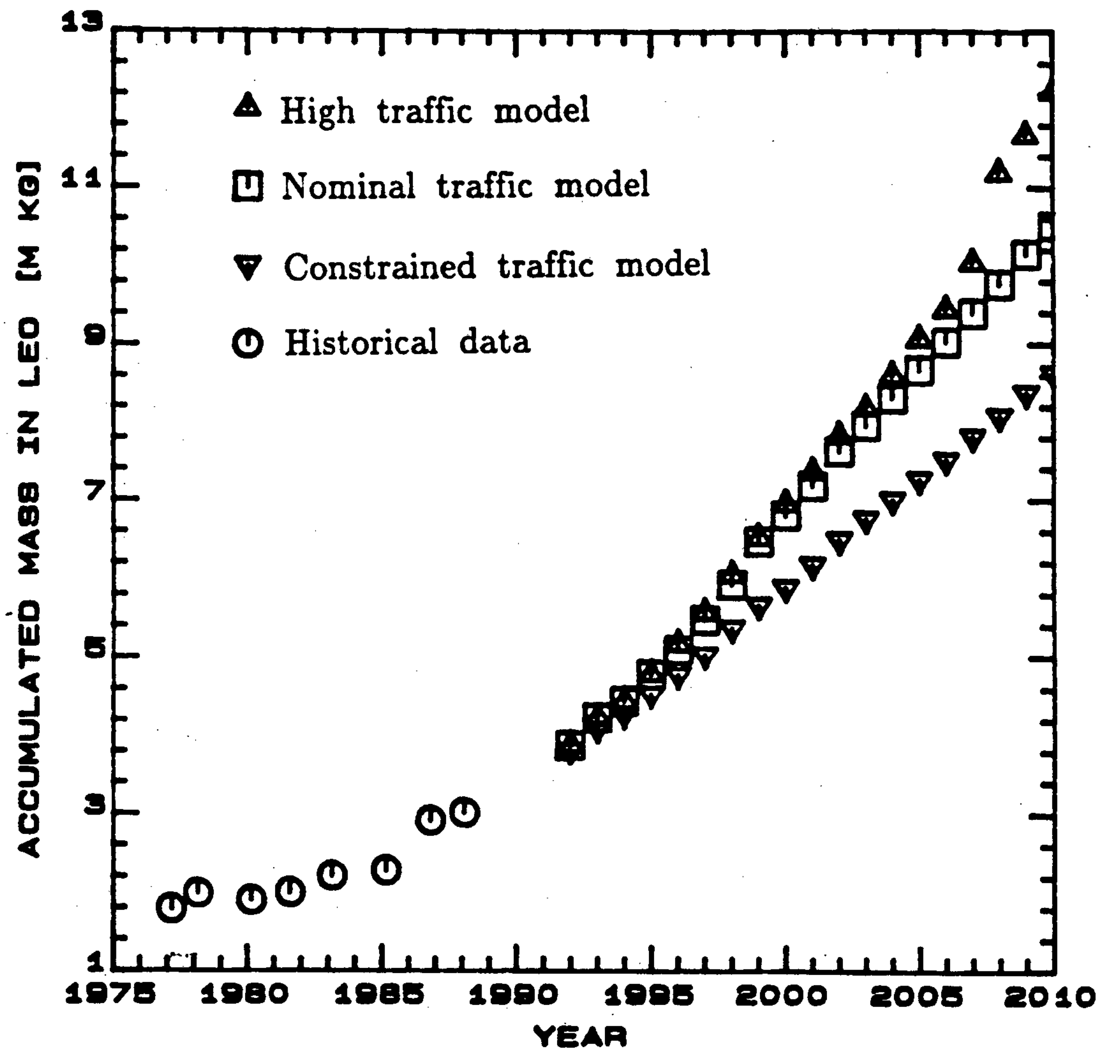

Figure 7: Projected Growth of Accumulated Mass in LEO

NOTE: Because the size, shape and mass of cataloged objects in orbit vary to such an extreme, mass in orbit was chosen as the most representative variable.

Mathematical models indicate that a continuing escalation of the nominal traffic model with no further debris controls could lead to a critical density sometime before the middle of the 21st century, and an unstable environment could occur sometime in the latter half of the 21st century, depending on what actions are taken after the critical density is reached. Once a critical density is reached, the only alternative for stopping a runaway is to increase the rate at which objects are removed from the environment. Using today's technology, this would require the expensive technique of retrieval.

There is some uncertainty in these predictions. As to whether a simple continuation of the nominal and constrained traffic models, with no increases in efforts to moderate debris, will lead to a stable or unstable environment is not entirely clear. In any case, it is clear that efforts to moderate debris generation would result in a less hazardous environment.

Reducing uncertainty in predictions about the future environment would require improving the fidelity of existing models.

Regarding the situation in both LEO and GEO, although significant uncertainties exist, the following conclusions, if current trends continue, seem unavoidable:

(1) Collisional breakup of space objects will become a source for additional orbital debris in the near future, possibly before the year 2000.

(2) Over a longer period of time, the orbital debris environment will increase with time, even though a zero net input rate may be maintained. Ultimately, this could lead to a stable but hazardous situation or, worse, an unstable environment with a subsequent cascading effect.

The discussion in the preceding paragraphs has been limited to LEO. The situation is considerably different in GEO. There are currently about 453 cataloged objects that traverse GEO altitudes, of which only about 150 are geostationary. The others are in either geosynchronous or semi-synchronous, highly elliptical ("Molniya") orbits. The average spatial density of objects is 2 to 3 orders of magnitude less than in LEO, so that the likelihood of a collision is not significant at present. However, local "bunching" of satellites in at least six prime service locations can increase collision probabilities by factors of 100. Nonetheless, the relative velocities are inherently low. Even GEO transfer stage velocities are below 2 km/sec. Hence, the near-term concern for debris in GEO is less compelling than for LEO.

D. Light Pollution

Astronomers are now beginning to experience problems in their work because of debris effects. There have been cases of confusion about whether an object observed is an item of scientific interest or a piece of debris. Additionally, as the debris population grows, the amount of light reflected by the debris also grows. In a field where minute differences in degree can have significant meanings, such "light pollution" of the sky can hinder astronomical efforts.

II. IMPLICATIONS

The probability of collision is a function of the spacecraft size, the orbital altitude and the period of time that the spacecraft will remain in orbit. The orbital debris environment in LEO presents a problem even now for space operations which involve large spacecraft in orbit or satellites in orbit for long periods of time. A "space station" is the primary example of such a spacecraft, and it will be necessary to shield it over large areas in order to achieve the design safety criteria.

The "design driver" is the determination of an acceptable level of risk. For example, the specified level of risk for manned space programs from Apollo to the present has been essentially constant at .005 probability of penetration over the lifetime of the space system. The actual level of risk experienced by these spacecraft has been significantly less than that specified because other design requirements made the spacecraft more robust. The earlier manned space programs addressed only the natural meteoroid environment but the current shuttle and proposed space station requirement addresses both the natural meteoroid and the orbital debris environments. Substantial growth of the debris environment may also require additional shielding for smaller satellites.

In order to visualize the implications of orbital debris growth, it is helpful to consider two illustrative cases. One is a "space station" of the general size of the future Space Station, operating at 500 km. The probabilities of impact are approximate, based on equivalent surface area and do not account for: directional effects and the relative orientation of component elements. The other is a typical small satellite operating at the LEO most popular satellite altitude of 800 km. For each of these cases, we will compare the effects of the current debris environment with the effects of the increased debris environment which will result if growth of the tracked population continues at a rate midway between the nominal and constrained traffic models shown in Figure 7.

A "space station" case for the 1988 debris population is illustrated in Figure 8. The average number of impacts per year is plotted against the debris object size in centimeters. Inspection of the figure shows that in the 1988 environment the chance of a 1 cm or larger object striking this "space station" is predicted to be one possibility in twenty years. It would be necessary to take protective measures for this "space station," shielding it for objects at 1 cm and smaller, and either accepting the low probability of impact by a larger object or by providing collision avoidance for larger objects. This is the case even if there were to be no growth of the current debris population. Impacts with objects too small to cause penetrations or other significant structural damage will be much more frequent. About 50,000 impacts of .01 cm particles would occur each year. Surface erosion could occur as a result, which may be a problem for some sensitive surfaces, such as optics or solar panels, over the lifetime of the Space Station.

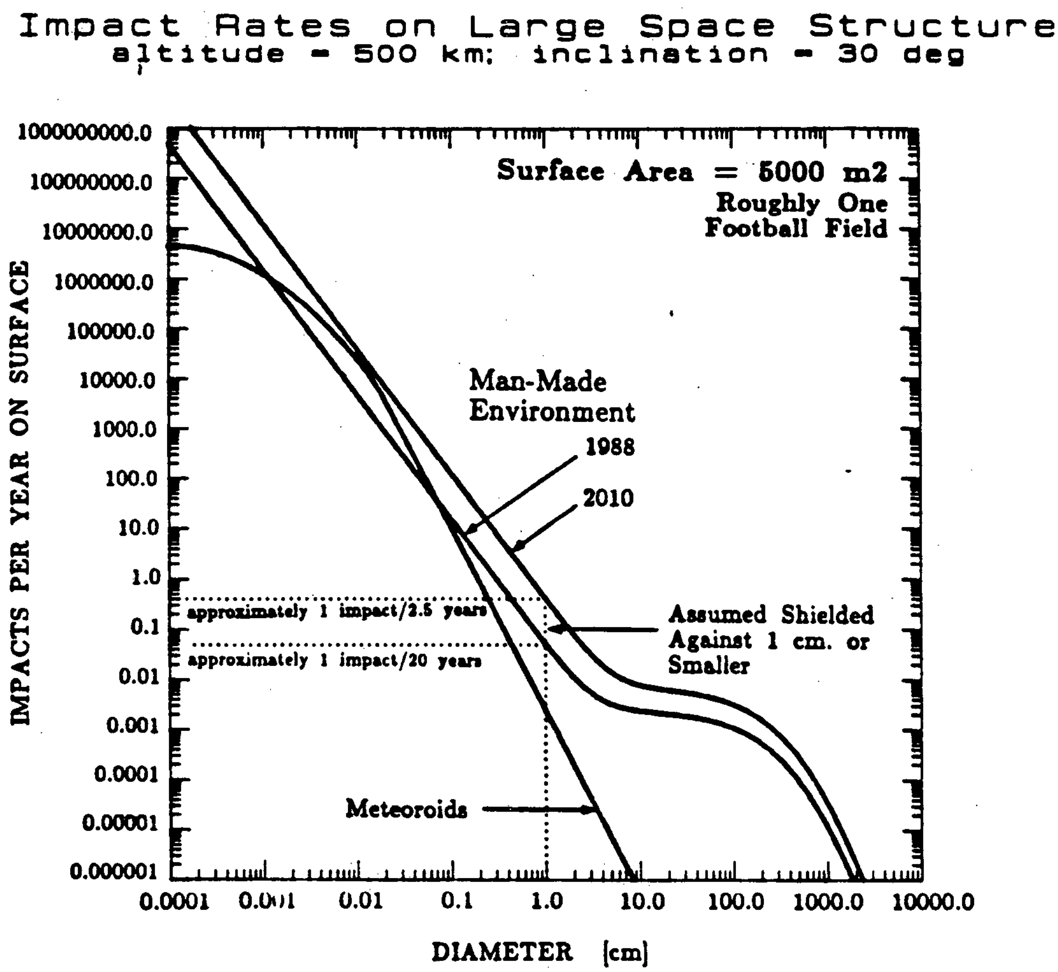

Figure 8: Orbital Debris and Meteoroid Impacts on a Large "Space Station" Class Spacecraft - 1988 & 2010

The impact rate on this "space station" for the projected 2010 population is also shown in Figure 8. The probability of a 1 cm or larger object striking the "space station" in the 2010 environment is predicted to be one possibility in two years. Collision avoidance maneuvers would become five times more frequent. If the 0.01 cm and smaller debris population grew as projected, erosion of protective surfaces designed to minimize atomic oxygen attack could become a serious problem.

The small satellite case for the 1988 debris population is illustrated in Figure 9. Inspection of this figure shows that in such an environment, the chance of a catastrophic collision with a 1 cm or larger object is predicted to occur once in 950 years. Only erosive effects due to smaller debris impacts are significant for spacecraft operation in this case. A few hundred or thousand impacts of debris smaller than 0.01 cm. will occur each year. Surface erosion could be a problem for sensitive surfaces. The lower probability of significant impact is because the exposed area of this spacecraft is more than two orders of magnitude less than a "space station," even though the debris environment at 800 km is five times more hazardous than that at 500 km.

The effect of population growth by the year 2010 on the typical small spacecraft is also illustrated in Figure 9. At that time, the chance of a catastrophic collision with a 1 cm or larger particle is predicted to be one in 110, which is still not a major concern for most spacecraft. However, about ten 0.1 cm particles will strike the spacecraft each year, which will make some form of shielding or some other form of protection technique mandatory. Surface erosion rates will be increased an order of magnitude, which could produce problems for optical surfaces.

Another very important consideration is extravehicular activities (EVA), since crewmen are exposed to the debris impact risk during extravehicular operations. The risk is a function of the exposure length and the capability of the EVA suit to resist impact events. The primary hazard is significant growth in small debris due to hypervelocity collisions. As the environment becomes a greater threat, the suit design requires greater structural capability to maintain a specified level of risk. Such increased structural capability can compromise the crewman's mobility and EVA effectiveness.

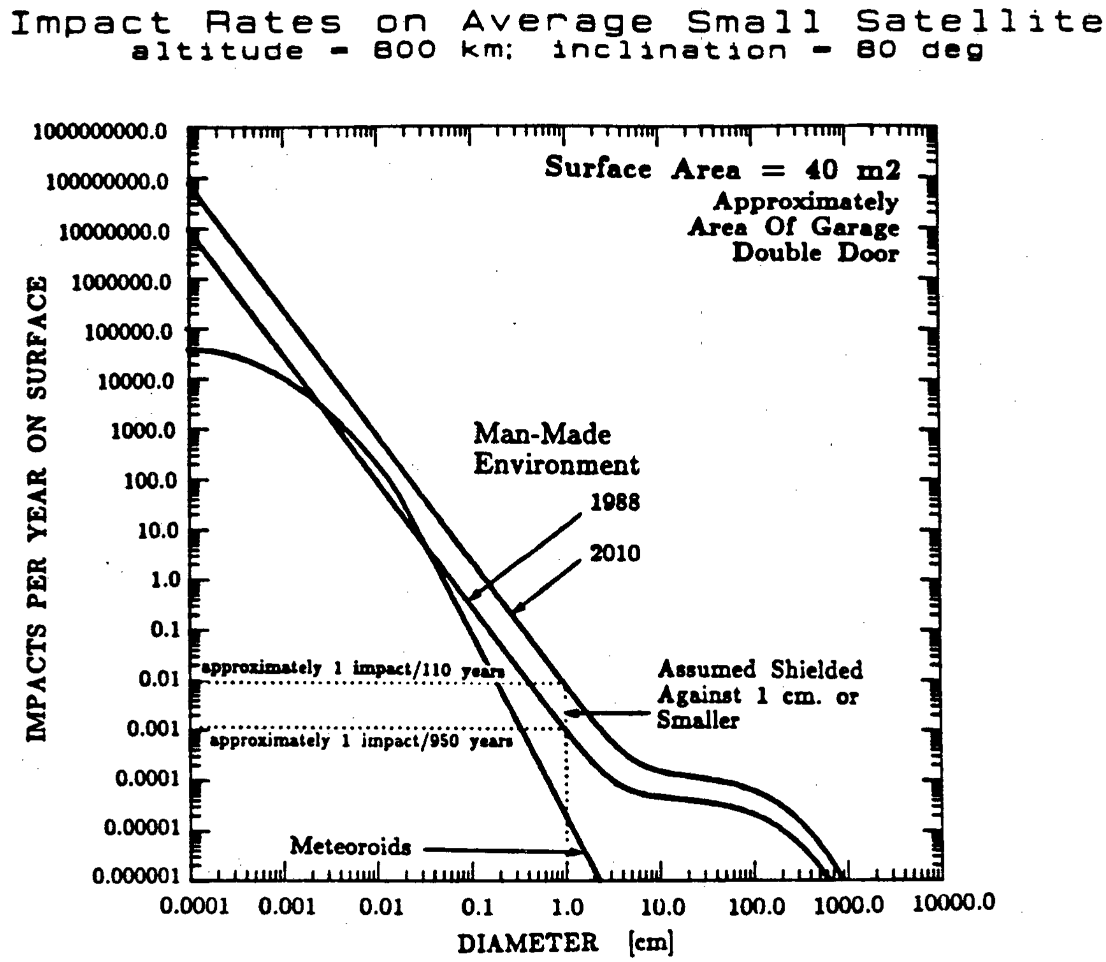

Figure 9: Orbital Debris and Meteoroid Impacts on Small Spacecraft - 1988 and 2010 Environments

PART TWO: CURRENT POLICIES AND ACTIVITIES, OPTIONS AND ASSOCIATED RESEARCH NEEDS

INTRODUCTION

Although agency policies concerning orbital debris are only just forming, orbital debris considerations have already caused changes in the plans and activities of some agencies. Some policies and activities are motivated by the need to protect a spacecraft; others are designed to prevent debris proliferation. Efforts have come in four distinct areas. First, preliminary research is underway to define the debris environment more precisely. Second, ways to reduce data management limitations are being explored. Third, several operational procedures are being adopted to limit growth in the debris population. Finally, the design philosophies for future missions and spacecraft are beginning to address debris considerations.

In addition to describing current policies and activities, the chapters in Part Two discuss a variety of options for better defining the debris environment and affecting changes in designs and operations so as to reduce the threat posed by orbiting debris. The chapters also identify research and development efforts required to provide the technologies essential to accomplishing these options. Chapter 3 describes existing national and agency policies concerning orbital debris. Chapter 4 discusses what can be done to better define the orbital debris environment through improved monitoring. Chapter 5 discusses how to improve our ability to handle the vast data processing and data base maintenance requirements associated with defining the debris environment. Chapter 6 addresses ways to minimize debris propagation through launcher and spacecraft design and operational procedures. Chapter 7 discusses options for surviving the debris environment that are available to any user of space, recognizing that the debris population will continue to grow even as actions are being implemented to reduce the rate of growth. In each of these discussions, one must recognize that few of these policies or actions can be wholly effective without cooperative efforts by other spacefaring nations.

CHAPTER 3: EXISTING POLICIES CONCERNING SPACE DEBRIS

I. NATIONAL SPACE POLICY

The National Space Policy, signed by President Reagan in February 1988, included a statement that "all space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness." Except for this single statement, no comprehensive national policy concerning orbital debris currently exists. (The U.S. is a signatory to the Liability Convention of 1972; however, this multinational agreement does not specifically address orbital debris. See Chapter 9, Legal Issues.)

II. LIMITED AGENCY POLICIES

Similarly, comprehensive agency policies or commercial regulations concerning orbital debris currently do not exist. America's space program is divided into two categories: government programs affected by law, administration policies and internal agency directives; and commercial programs affected by law, regulation, and licenses. Each category is affected by different processes, constraints and philosophies. There are some limited policy statements and regulating mechanisms, however, which address some debris considerations. Also, *de facto* policies exist through the adoption of debris-mitigating procedures or philosophies. Examples of limited policies are:

(1) Perhaps the most significant debris-reduction policy has been the NASA requirement instituted in 1982 for the venting of the unspent propellants and gases from Delta upper stages to prevent explosions due to the mixing of fuel residues. No U.S. hypergolic stages have inadvertently exploded in space since the institution of this requirement.

(2) DoD Space Policy, issued in February 1987, broke new ground by expressly addressing orbital debris as a factor in the planning of military space operations. This guidance was also included in the recent national space policy for all space sectors. Both policies call for positive efforts to minimize the creation of space debris. The DoD space policy states:

> "DoD will seek to minimize the impact of space debris on its military operations. Design and operations of DoD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements."

(3) Air Force (AFSC, Space Division) regulation SDR 55-1 directs program directors and managers to adjust satellite development and deployment plans to avoid orbital positioning problems. It applies to initial satellite placement and subsequent repositioning. That is, level of congestion must be considered when planning a final orbit location or transfer. This refers to both geosynchronous as well as lower altitude satellites.

(4) NOAA and several DoD programs boost their satellites which are no longer functional into orbits above GEO to prevent the creation of additional debris by inadvertent collisions with drifting satellites and to free valuable orbital slots.

(5) All commercial activities subject to DOT's authority are subject to the Office of Commercial Space Transportation's regulations established in Chapter III, 14 CFR Part III. These regulations require each applicant to address safety issues with respect to its launch, including the risks of associated orbital debris, on-orbit safety, and reentry hazards.

(6) The FCC has requested comment from its Advisory Committee for ITU WARC-ORB-88 on the need for the regulation of the removal of satellites from the GEO following expiration of useful life. The Committee indicated that the current practice of some satellite operators is to use onboard fuel to boost retired satellites above the GEO at the expiration of the spacecraft's useful life. Furthermore, because current understanding of the GEO environment indicated that the possibility of space collision with a retired spacecraft was remote, the Committee stated that the benefit of legal and compliance verification regimes would not justify the cost. The Advisory Committee further noted that this appears at present to be either a non-problem or one that would be addressed more cost-effectively on an ad-hoc basis. Based on these comments, the FCC determined that the problem was not of sufficient magnitude to warrant the adoption of formal rules at this time.

III. FURTHER ONGOING EFFORTS

There is a growing recognition within the Federal government that more formal mechanisms need to be established for addressing debris considerations. Efforts to define the problems and to identify options for dealing with them are expanding. For example:

(1) NASA has created an in-house Orbital Debris Steering Group to examine potential NASA policies and procedures and to make recommendations to the Administrator as to proper

approaches to orbital debris problems. Basic and applied research about debris impact behavior and spacecraft shielding is ongoing to provide input to both policy formulation and the design of the U.S. Space Station and other spacecraft.

(2) DOT conducts research activities at the Transportation Systems Center and its contractors. A recent report, entitled "Hazard Analysis of Commercial Space Transportation (Vol. I: Operations; Vol. II: Hazards; Vol. III: Risk Analysis"), devotes explicit attention to orbital and reentry hazards, and to the management of space debris hazards. Current research is aimed at comparing the relative operational space safety and debris type/number characteristics for existing commercial ELVs, both generically (e.g., typical parking and GTO orbits, and orbital life of operational debris) and for specific proposed missions. Further research focuses on the development of rational, risk-based insurance requirements and regulatory standards for the commercial space industry.

(3) DoD and NASA are jointly working on the Smart Catalog, an effort to define the orbital debris environment. The current Space Surveillance Network (SSN) discretely tracks space objects greater than 10 cm. Smaller objects cannot be discretely tracked, but can be statistically modeled. These two different types of information form different types of data bases. The Smart Catalog will combine these data bases into one hybrid data base.

(4) DoD and NASA maintain a continuing effort to understand the debris hazard and model the effects of explosions and collisions. The research aids satellite and booster program offices by assessing vehicle-specific debris hazards and debris abatement options.

(5) Operating under the Space and Missile Test Organization (SAMTO), DoD has established a tri-service Space Test Range Organization to coordinate and oversee the safe conduct of testing performed in space by SDIO and the Services. A key objective is better control of proliferation of space debris by institutionalizing the support elements previously organized for each test.

CHAPTER 4: MONITORING THE DEBRIS ENVIRONMENT

I. CURRENT ACTIVITIES AND RESEARCH

The Space Surveillance Network (SSN), which is operated primarily by DoD, is tasked to monitor man-made objects in space. The primary function of the missile warning sensors within the SSN is to track earth orbiting objects in order to allow the missile warning radars to distinguish between orbiting objects and incoming missile attacks. To accomplish this task, a world-wide array of sensors has been established. The observations from these sensors are compiled into a single database and its associated document--the Satellite Catalog. There are currently over 7,000 objects large enough to be detected, tracked, and cataloged. There are perhaps millions more objects that are too small to be detected and tracked consistently. The SSN sensors provide positional data on the objects and a rough approximation of size. Using data from these and other sources, various characteristics about the debris are studied, including radar reflectivity, shape, mass, velocity and orbital inclination.

Figures 10 and 11 shows the location of the SSN sensors. These sensors can be divided into two categories: 1) radars, used for detection and tracking of objects in both LEO and GEO and, 2) optical, used primarily for detection and tracking of GEO objects. At GEO altitudes, the detection capability of optical systems is significantly better than that of radar systems.

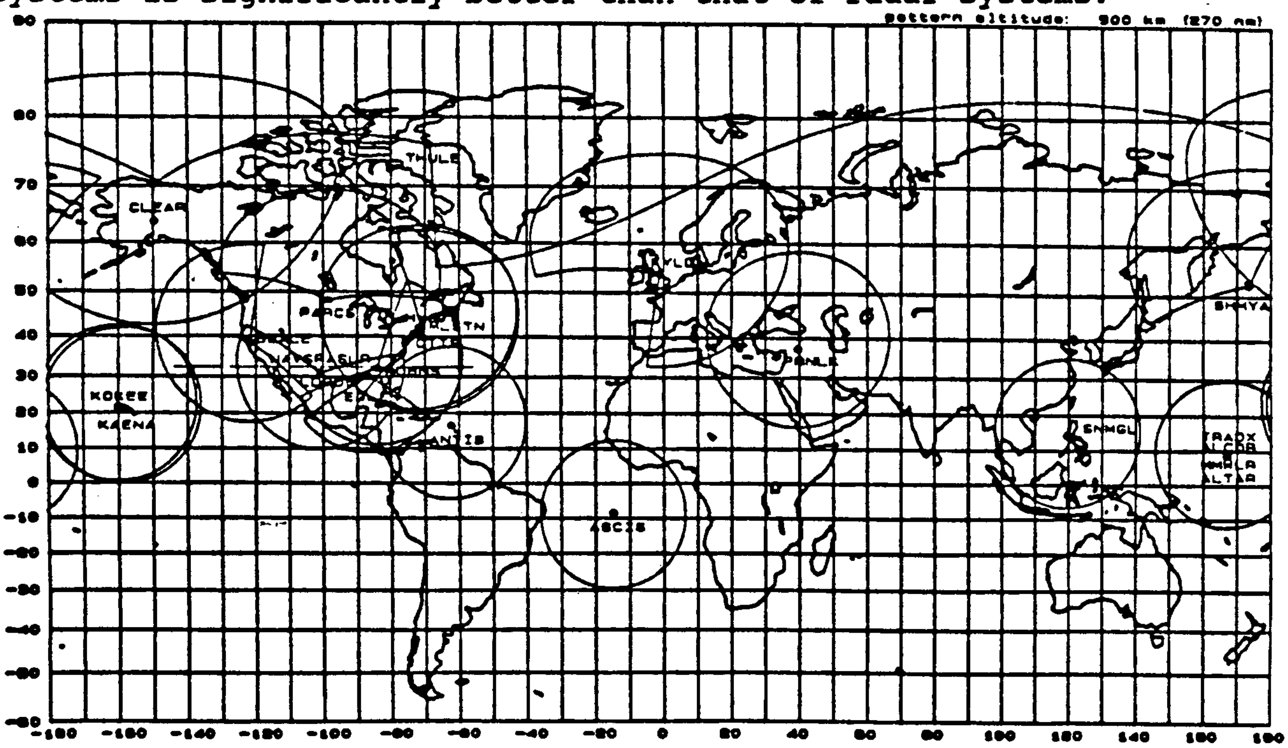

Figure 10: Space Surveillance Network (SSN) Radars and Their Field of View at 500 km.

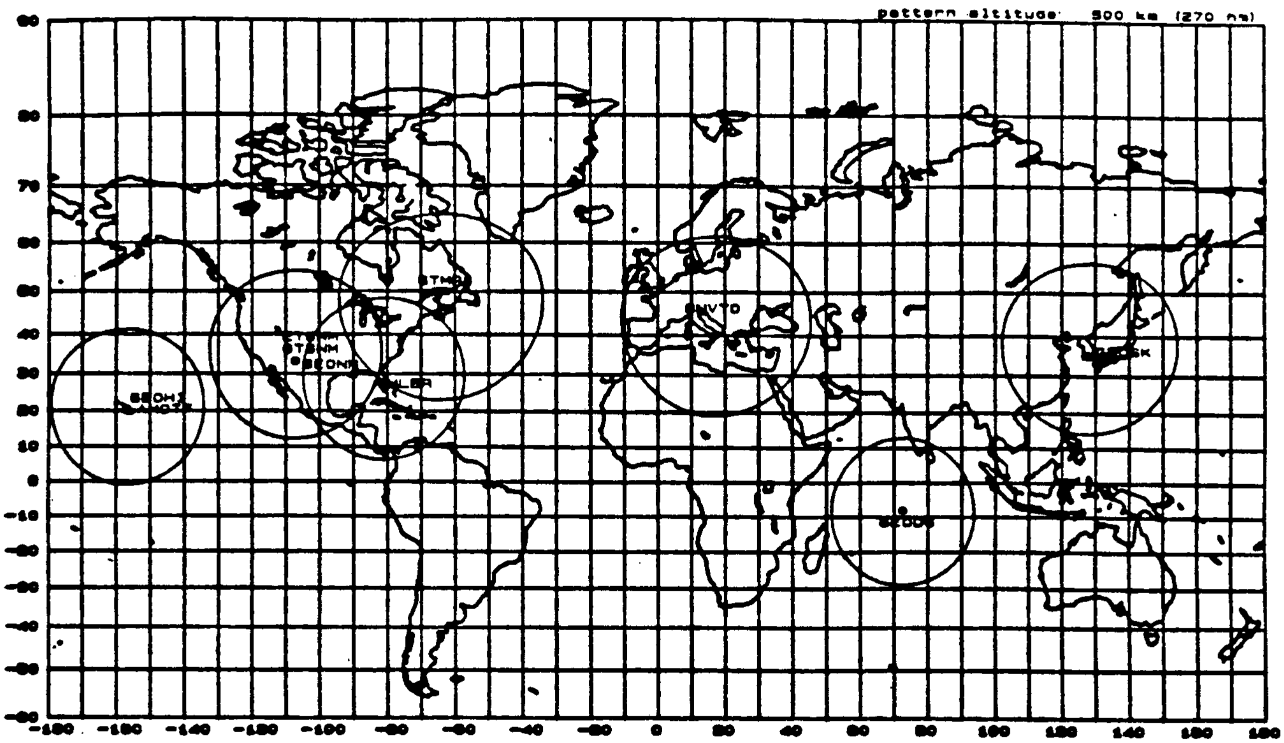

Figure 11: Space Surveillance Network (SSN) Optical Sensors and their field of view at 500 km

Figure 12 shows the altitudes covered for each category of sensor, and the size of objects each is capable of detecting. Observations gathered from these sensors are used in developing a model of the debris environment and its behavior. This model is then used to predict various trends and measurements. As the figure illustrates, the minimum size object that can be detected is about 10 cm diameter. For a given type of sensor (radar or optical), the higher the altitude of an object the larger the object must be for the SSN sensors to track it. This limitation is significant due to the estimated large number of objects smaller than this size threshold.

Other limitations significantly affect the SSN capability to detect and track orbital debris. The limitations of the current data management capability are discussed in detail in Chapter 5. The limitations due to a lack of resource availability are created by an already overtasked SSN. By employing special techniques, SSN sensors could be used to detect smaller orbital debris objects; however, these techniques involve the use of SSN sensors for extended time periods (over 4,000 hrs), which places an extreme burden on the normal SSN mission.

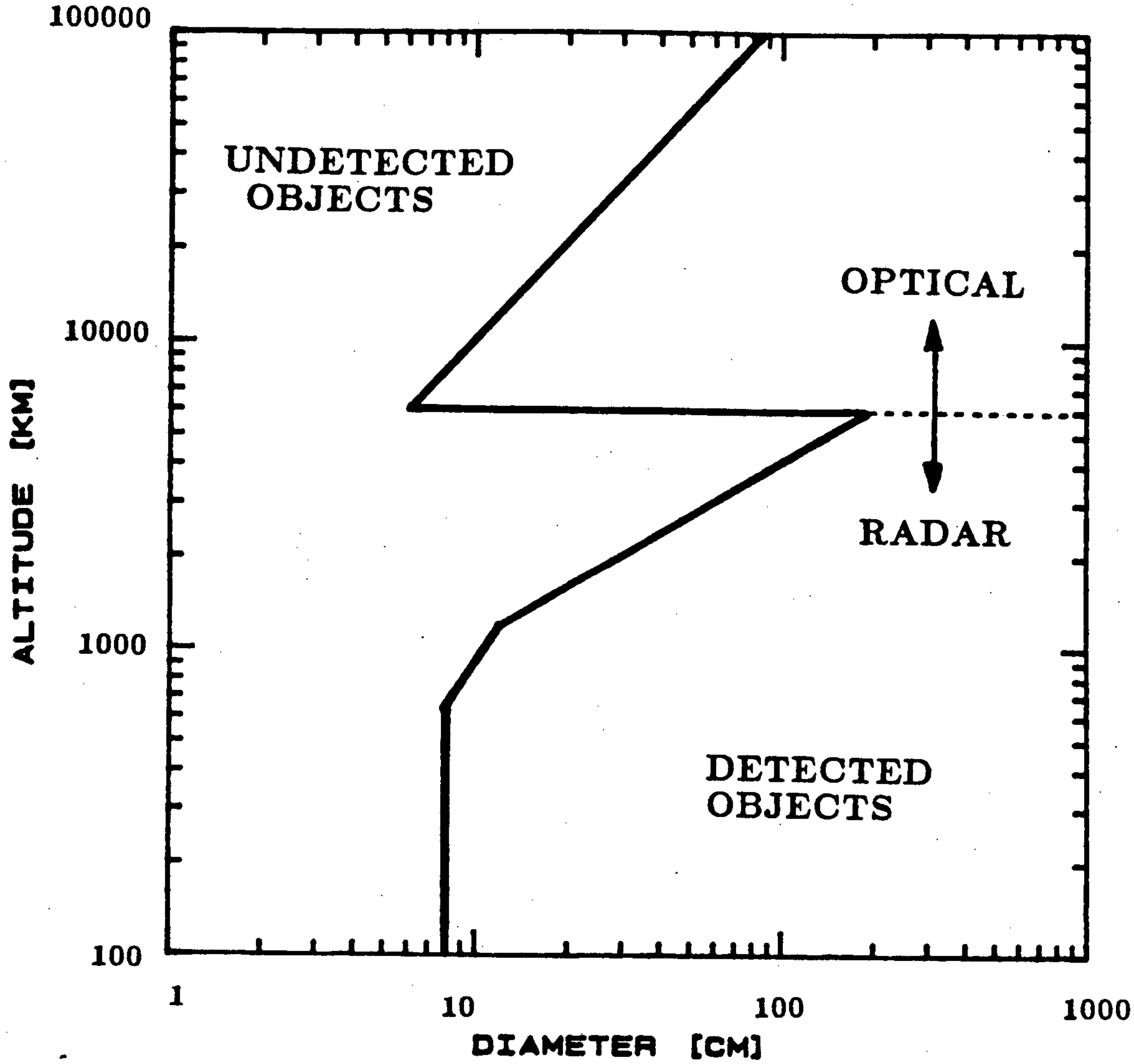

Figure 12: Sensor Altitude Limitations

Because of current detection limitations, observation data inputs to the models are limited. The lack of data on small objects necessitates reliance on modeling of breakup events, which are a major contributor to the small debris population. Therefore, it is necessary to study breakups in detail, both experimentally and theoretically, in order to satisfactorily model the small debris environment.

Collision analysis studies, currently underway, provide the capability to examine breakup phenomena under laboratory conditions. Refinements in these studies could provide input data for modeling the effects of hypervelocity satellite collisions and for making risk assessments. Because impacts in low earth orbit occur with an average speed of 10 km/sec, specialized equipment (such as a hypervelocity gun) is needed to create and monitor realistic impact events. Current and future studies include: (1) gun research and development, (2) hypervelocity impact research testing, to determine the effect of collisions on various materials and spacecraft structures configurations, (3) hypervelocity impact modeling, and (4) spacecraft sub-system and component impact testing and analysis.

II. OPPORTUNITIES FOR IMPROVEMENT AND FUTURE RESEARCH

Several options are available to improve the detection, tracking, and monitoring capabilities of the SSN. Technology exists to allow us to increase the number of objects which can be cataloged and also to begin statistically characterizing the debris population in earth orbit. A combination of approaches including modifications to existing ground based sensors, development of space based space surveillance, and new data management and data processing concepts may be necessary.

A lead role for USSPACECOM in the operation of ground- or space-based radars to track orbital debris is desirable in view of the current USSPACECOM mission, ongoing development projects and current tracking capabilities, and is a prudent step necessary to avoid duplication. A lead role for NASA in modeling and statistical analyses of debris measurements is desirable in view of its expertise, experience and ongoing projects in these areas.

In considering the development, modification, deployment, and employment of sensors, it will be necessary to ensure that there are no conflicts with international obligations, in particular the ABM Treaty. Proposals which may be affected by Treaty provisions should be reviewed by appropriate compliance authorities, such as the DoD Compliance Review Group. For example, the Treaty contains restrictions on large phased-array and early warning radars; consequently, proposed improvements to ballistic missile early warning radars should be reviewed to ensure they are not inconsistent with these restrictions.

A. Evaluate and Exploit Existing Capabilities

(1). Studies of Measurement Capabilities The existing Space Surveillance Network sensors are used to a limited extent to take measurements of the orbital debris environment. A study could be conducted to determine the potential contribution of each sensor to an operational, smaller size debris monitoring system. A study group consisting of DoD, MIT/Lincoln Laboratory and NASA could conduct the effort.

(2). Trade-off and System Studies If the study of the current space surveillance sensors shows inadequate capability to collect orbital debris data, the value of upgrading existing sensors must be investigated. As a minimum, the following factors need to be considered in this study:

a. Impact of adding the debris data collection mission to the primary mission of existing sensors.

b. Cost and technical trade-offs associated with making the necessary modifications to enable the Space Surveillance Network to collect orbital debris data at a higher rate.

This study effort to include preparation of a debris data collection plan could be led by DoD with participation by MITRE, MIT/Lincoln Laboratory, and NASA.

(3). Debris Measurements If the Space Surveillance Network can contribute resources to debris measurement, designated sensors could begin collecting orbital debris data to the extent that primary sensor missions are not impaired. This data collection effort would support a study, the purpose of which is two-fold:

a. To begin baselining the debris environment in low earth orbit as soon as is practical, and

b. To empirically assess the Space Surveillance Center's ability to process and analyze this type and quantity of data.

This study could be conducted by DoD, with data analysis responsibilities shared by DoD, NASA and MIT/Lincoln Laboratory. Analysts at all the agencies are already highly tasked; consequently, staff augmentation or use of contractor support may be required. The data collection effort and follow-on study could begin immediately after completion of the trade-off and system studies.

B. Expansion of Existing Capabilities - Radars

(1) Increase Power on Existing Collateral Radars Increasing the power output of a radar will increase its detection capability. With increased power, a radar could either detect smaller objects or detect at increased ranges or a combination of both. However, increasing the output power of a radar generally is not easy and is impossible for some systems. In any case, a power increase for a radar would be a costly modification.

Implementation of this option would require hardware additions to existing sensors. Increased power could also have adverse impacts to environmental concerns, and could provide more data than can be handled by the data management system.

(2) Debris Environment Characterization Radar (DECR) Both NASA and MIT/Lincoln Laboratory have suggested using a narrow beam radar to begin physically defining the debris population in low earth orbit. NASA suggests developing a relatively small radar to statistically characterize small debris objects (1.0 cm or larger) at 500 km altitude on a routine basis. NASA's interest in developing this radar arises from the requirements to provide criteria for collision avoidance and for spacecraft shielding design for the planned Space Station.

This radar would help to validate the models currently being presented as "representative of the debris environment". Further, such a radar could conceivably help with early monitoring of breakups and serve as a supplementary method for determining the sources of small debris. By mapping the distribution and density of debris clouds, it could begin to verify the differences in cloud propagation resulting from collisions versus explosions. A dedicated debris radar could also alleviate problems of trying to obtain observation time on already heavily used tracking radars.

The development effort could be relatively minor since the proposed system consists of off-the-shelf hardware. Also, siting the radar with other SSN assets could reduce site preparation and support requirements. It is uncertain who would provide long-term operations and maintenance support in the budget process and how the site would be selected. Funding has been approved for the preparation of the Request for Proposals (RFP). NASA has planned to incrementally fund the development and fabrication of the radar.

The radar should be located as near to the equator as possible (preferably between 0 and 7 degrees latitude) to permit observation of debris regardless of orbital inclination. It would enhance effectiveness to locate the radar near an existing radar to permit the identification of larger objects within the sidelobes of the DECR by means of cross correlation and checking between the two radars. NASA could be the lead agency for design and construction of this radar.

While the DECR will be adequate to provide the data needed in the near term, it is expected that data on smaller particles and data on the debris population in GEO will be needed in the long term. For these purposes, development could be pursued of an orbital debris radar which can operate at a shorter wavelength (perhaps Ku band, 1 cm wavelength), higher power, and with a larger antenna.

(3) MIT/Lincoln Laboratory Small Object Identification Lincoln Laboratory suggests the Haystack long range imaging radar in Massachusetts can be used, on an as available basis, to gather the same type data that a DECR could produce. Lincoln used the Haystack radar in that mode during early FY 88.

If Haystack operational requirements would allow, studies could begin immediately. The Haystack radar also has the added benefit of being collocated with the Millstone radar, which could be used simultaneously for verification and to perform multi-sensor experiments.

Use of the Haystack radar for debris characterization would compete with other government and scientific agencies' needs for the radar. Lincoln Laboratory estimates that it would take a total of 4800 hours of radar operation to characterize the present debris population, which is far in excess of available viewing time. Also, the location of the Haystack radar (42 degrees above the equator) is not ideal for tracking objects in low inclined orbits. Haystack's viewing potential for objects in lower inclined orbits in LEO is limited by: the increased range to the object, the relatively short time that a potential object would be in view, and the increased signal attenuation and distortion caused by looking south through the atmosphere.

While tasking for occasional experiments may be practical, adequate hours may not be available for necessary debris tasks, given the priority of other tasks. DoD could be the lead agency for Haystack studies.

(4) Reentering Debris Radar (REDRAD) To determine the rate of elimination of debris from the environment by drag and subsequent reentry, and to determine the net effect on the orbital debris burden, an experimental measurement of the total rate of debris reentry is required to help validate debris population models. The REDRAD data can be used to calculate the total reentry rate of debris.

Radars have long been used to detect the ionization trails caused by the high speed entry of meteors into the earth's atmosphere. Reentering debris also produces ionization trails, which can be detected by meteor radars. Reentering particles as small as 10 grams (corresponding to about 2 cm diameter) were detected by a modified meteor radar during the Delta 180 test. By operating the radar at highest powers, particles as small as 0.1 cm could be detected.

Distinguishing between trails caused by naturally occurring meteors and those caused by debris requires measuring their velocity, which is less than 7 kilometers/sec for reentering debris, and always greater than about 11 kilometers/sec for meteors. A high-power version of REDRAD which incorporates the capability for velocity measurement is currently under consideration. NASA could be the lead agency for this effort.

(5) Other Radars (Foreign and Domestic) The National Astronomy and Ionosphere Center at Arecibo, Puerto Rico, operated by Cornell University for the National Science Foundation uses an S-band transmitter for ionospheric heating experiments. This transmitter could be used to monitor orbital debris, although the size of debris detected would be limited by the radar wavelength. NASA is currently conducting experiments with the Arecibo facility and has demonstrated that orbital debris can be detected at sizes on the order of 1 cm or possibly less.

The U.S. Army is planning a ground-based experimental radar (GBR-X) for construction at the Kwajalein Missile Range, with completion scheduled during the 1990s. The primary function of this radar will be military research and development, but it is expected that some operational time will be available for debris monitoring. The location of this radar at about 9 degrees latitude would make it useful for measuring debris in low inclination orbits.

With the exception of the Soviet Union, no foreign country has a major capability for tracking satellites and orbital debris. However, some individual radars exist which could provide supplemental data. These radars could monitor breakups, especially during the period shortly after the breakup, when a large number of objects are in close proximity. Other cooperative projects are possible. The West German government has indicated interest in developing orbital debris projects involving their satellite tracking radar. Japan also has a satellite tracking capability that may be of some use. International cooperation of this kind not only provides useful data, but also raises international awareness of the orbital debris problem. NASA, in cooperation with the State Department, is the current lead in pursuing cooperative international efforts of this type.

(6) Space-based Debris Radars A space-based radar to monitor the debris environment could provide accurate velocity and direction measurements, and has the potential for detecting small debris sizes on the order of 1 mm within a few kilometers of the spacecraft. However, radars this sensitive would require significantly more power to operate than optical systems of comparable sensitivity. As a consequence, current space power technology would limit the capability of space-based radars to levels less than optical sensors. As new radar or power technologies develop in the future, the achievable capabilities of a space-based radar may exceed those of optical systems.

C. Expansion of Existing Capabilities - Optical Sensors

(1) Ground-based The existing SSN optical systems are intended for tracking satellites above 5,000 km altitude. However, they are inherently capable of detecting orbital debris at lower altitudes, with a limit of about 5 cm at 500 km altitude. The use of these sensors to provide statistical debris flux data at altitudes below 5,000 km can be explored.

Incorporating new Charge Coupled Device (CCD) technology into existing SSN optical systems could improve the detection and track capability in GEO. This requires the addition of hardware and will likely be implemented through current efforts. This relatively low cost option will add lifetime to the current systems and provide an increase of about 10 times greater sensitivity, allowing smaller or more distant objects to be tracked.

NASA has also used a small, inexpensive, portable, image-intensified 20 cm telescope for looking at debris from recent breakups that could not be seen at low latitudes. This system is being upgraded to a larger aperture (30 cm) and fitted with a CCD detector to provide a sensitivity equivalent to the current SSN optical system.

Optical sensors measure the sunlight reflected or scattered from objects in orbit. In order to interpret these data in terms of geometric size of debris, the reflectivity of the object must be known or estimated. A series of measurements of albedo, or reflectivity, of debris objects is required in order to establish statistical data on the means and standard deviations of debris albedos. These data can be obtained directly from comparison of infrared and optical signatures of an orbiting object, or indirectly from comparison of radar cross-sections and optical signatures. The sensors located at the DARPA Maui Optical Station could be used for this correlation. DoD could be the lead agency for SSN upgrading while NASA could be lead agency for improvements to their 20 cm telescope.

(2) Spaced-based For LEO, a major deficiency in our capability for orbital debris measurement is the inability to measure the debris population in the 0.1 cm to 10 cm diameter size range. Space based measurements have the advantage that they can be done close to debris particles and without having to observe through the atmosphere.

Several space-based surveillance studies and prototype developments are underway. Due to similarities, these systems will be discussed together. DoD has developed a prototype space based optical system (Defense Support Program Adjunct). The Jet Propulsion Laboratory (JPL) has also done a detailed conceptual design study of a satellite for debris monitoring (QuickSat).

NASA has done a detailed feasibility study of combined visible and thermal infrared optical system (Debris Collision Warning Sensors) to be operated from the Shuttle Orbiter bay. This experiment has entered detailed design phase. Other proposed space-based optical sensors are taking advantage of rapid advances in sensor technology.

The spacecraft necessary to carry a space-borne sensor depends on the mission profile. Options range from a dedicated space debris satellite to "piggybacking" sensors on another satellite, the Shuttle, or eventually the Space Station. Conceptual studies have shown that the dedicated debris satellite would be more costly to implement than the Shuttle-based experiment. The Shuttle-based experiment is capable of characterizing the LEO debris environment extensively for the date of flight.

Technologically difficult aspects of a dedicated space debris satellite include providing adequate on-board data processing, timely downlinking of data and a constantly changing point of reference. However, near-term systems riding "piggyback" on other high priority mission payloads save cost but may not provide the best orbit selection.

For GEO, a space-based optical sensor could significantly increase the ability to detect smaller debris sizes. Lower angular velocities in GEO would mean that an even simpler system would be required compared to LEO. In addition, a GEO - based system would only have to detect debris 10 cm and larger to provide new data.

Further studies, led by DoD, including engineering analyses and device designs, might be initiated.

D. <u>Returned Material Analysis</u>

(1) <u>Returned Spacecraft Surfaces</u> Material retrieved from the Solar Max Satellite has been a major source of new data on the small debris and meteoroid population for sizes below about 0.01 cm (100 microns). The small debris in this size range results from disintegration of painted surfaces on spacecraft and the firing of solid rocket motors in space. NASA could be the lead agency for analyzing the Solar Max materials.

(2) <u>Long Duration Exposure Facility (LDEF)</u> This structure was launched into LEO in 1984, and is scheduled to be recovered in 1989. LDEF represents a unique and major source of data for small debris. Based on model estimates, there should be several hundred impacts of meteoroids and debris with sizes up to 0.1 cm. A plan exists to examine the entire LDEF surface for impact craters immediately upon its return from space, to select

significant areas for further analysis and to assess other space orbital environmental effects such as ultraviolet irradiation, atomic oxygen erosion, etc. It is expected that the LDEF structure will be refurbished, fitted out with new experiments to form LDEF II, and launched into orbit again, sometime in the mid or later 1990s. NASA can be the lead agency for this activity.

(3) Witness Plates Experience gained from the Solar Max satellite material suggests that plastic witness plates may be useful, since traces of the impacting objects are better preserved in the softer material. A program of routine witness plate exposures could be planned for future Shuttle flights.

A problem with witness plate experiments in the Shuttle bay is that, because Shuttle flights are short duration, the period of time the plates are exposed to the space environment is so short that the number of impacts is relatively small. This problem could be solved by deploying a large area collector, which could be unfurled from the orbiter bay, and then at the end of the mission, furled again. A large sheet of thin plastic (mylar, for example) would be suitable. Conceptual studies of the experiment will be required. See Appendix 3 for private sector recommended experimentation. NASA could be the lead agency for this activity.

(4) Cosmic Dust Facility The NASA cosmic dust program routinely collects dust from the stratosphere by exposing collector surfaces to the atmosphere using high-altitude aircraft. Chemical and physical analysis has shown that a major fraction of the dust is derived from orbital debris which has reentered the atmosphere. An effort is needed to determine the amounts and origin of the dust from reentered debris. From this information, the total world-wide reentry rate of orbital debris can be estimated. This rate can provide a check on the theoretical estimate of the total reentry rate used in the debris environment forecast models. NASA can be the lead agency for this activity.

Additionally, the Cosmic Dust Facility is a major flight experiment planned for the Space Station. It will measure the velocity and direction of dust particles which impact the test surface. A fraction of these impacts will result from small orbital debris particles. Consequently, the facility could provide continuous detailed information on the small debris environment over its 25-30 year lifetime. NASA could be lead agency for this activity.

CHAPTER 5: MANAGING THE DATA

Data management limitations significantly affect the Space Surveillance Network (SSN) capability to detect and track orbital debris. This in turn affects our ability to accurately characterize the debris population and to develop options to minimize debris propagation and to survive the debris environment.

I. CURRENT DATA MANAGEMENT STATUS

The process of keeping track of large objects in space, conducted by DoD, involves three steps: 1) collect sensor observations, 2) correlate these observations to known objects, and 3) update the object database with the new observation. The database must be updated daily for all but GEO objects in order to keep an accurate and usable catalog of space objects. The correlation process is crucial to the overall process and commonly causes significant problems. Because measurement of small objects is not yet possible, monitoring them will require the use of a statistical database. Combining the large and small object databases will have to be accomplished through the use of a yet to be developed hybrid database that can accommodate both an empirical and a statistical database.

II. OPPORTUNITIES FOR IMPROVEMENT AND FURTHER RESEARCH

A. Data Bases

The ongoing acquisition and prototype development efforts described below can help create the rudiments of the data bases required in the future.

(1) SPADOC 4 One potential solution to the data base management problem is Space Defense Operations Center (SPADOC), block 4. The addition of SPADOC 4 would add capability to data base management and data base size, but not until the mid 1990s. New computer hardware will allow for cataloging of 30,000 on-orbit objects --this is about three times the current capability. SPADOC 4 is not currently designed to handle the vast volume of small debris data. This capability could be added.

Because SPADOC 4 is designed to handle discrete objects only, modifications to the current SPADOC software would be necessary to allow associated statistical debris data to be considered.

(2) Smart Catalog A proof-of concept for a hybrid data base, the Smart Catalog, has already begun. Smart Catalog combines the current discrete catalog data base and a statistical (for small untrackable debris) data base.

Smart Catalog can be done with current technology equipment. The proof-of-concept is showing great promise and the results should be available in early 1989. Although discrete tracking of all space objects--of significant size--is an ultimate goal of the SSN, this capability will not be available for some time. The Smart Catalog could provide an interim fix and allow a basic understanding of the total orbital debris environment. This understanding could provide a basis for operational decisions, such as which orbits/altitudes to use or how much shielding is required. Initially, the output of a Smart Catalog would only provide statistical or worried information on space debris. Thus, collision avoidance with orbital debris could not be accomplished with certainty.

Smart Catalog can be implemented in one of two ways. First, once the proof-of-concept is complete, the design specifications for the hybrid data base could be added to SPADOC 4. The second option could be to run Smart Catalog software on separate computers, off-line to the normal SSC computer system.

Smart Catalog could also be very cost effective. Data and data update requirements are significantly less for Smart Catalog than the discrete catalog. Computer hardware and software requirements are minimal. Sampling data, whether by a dedicated radar or by using existing radars, could be relatively inexpensive when compared to the requirements to discretely track tens of thousands of objects.

It should be noted that concepts such as the Smart Catalog have been created without the benefit of extensive debris data. Research to define further data base requirements must be conducted using empirical debris data. A study led by DoD could be conducted.

B. <u>Data Processing</u>

New and different data collection techniques which feed a hybrid data base will require that tremendous amounts of data be moved, stored, and archived. It will be necessary to explore alternative processing methods which can perform high volume object correlation and manage the statistical data base. The Uncorrelated Target Processor, or UCTP, is a DoD and MIT/Lincoln Laboratory prototype development which could significantly reduce the growing numbers of uncorrelated targets (UCTs) that currently bog down the SSN's data management capability.

However, comprehensive studies have not been conducted to examine implementation, loading on communications data lines, actual processing center requirements (may require an alternative/ subordinate center for processing), and command and control aspects associated with a debris monitoring capability. DoD could be the lead agency for exploration of this option.

C. Modeling

There is a need to characterize the orbital debris environment, even when observations are not practical, such as when the size or altitude of objects makes measurements difficult. Modeling, then, is required to combine existing measurements and theory in such a way that predictions can be made. Several types of models are required to make these predictions:

(a) A model to describe future launches, the amount of debris resulting from these launches, and the frequency of accidental or intentional explosions in orbit (traffic model),

(b) A model to describe the fragment size and velocity distribution which results from a satellite explosion or collision (breakup model),

(c) A model which will make long-term predictions of how debris orbits will change with time (propagation model), and

(d) A model which predicts collision probabilities for spacecraft (flux or risk model).

Many of these models exist; however, most were formulated to handle a relatively few orbiting objects for a short time and for a specific application. Consequently, current computer resources (hardware and software) are inadequate to handle the large number of objects associated with orbital debris, the long-term predictions required, and the variety of applications for which the models must be used.

Modeling being conducted at NASA has reduced the computational requirements considerably; however, greater improvements are required in event (breakup) models and environmental (propagation) models for both LEO and GEO. Modeling could be a joint NASA/DoD effort.

D. Validation and Analysis

Models of an environment or a process must be tested empirically for accuracy and predictability. If the output of the models does not match the real world, or if the predictions produced by the models are not repeatable each time the model is run, the model is not valid and it must be reformulated. To validate the models, then, test scenarios must be developed to allow empirical data to be compared to model results. The tests normally involve collecting a limited set of data, where possible, and comparing the data set to the model results, having run the model under the same conditions as the collected data. These tests not only validate models but also serve to refine the models for increased accuracy. This validation method certainly applies to debris models. Since several organizations have ongoing debris modeling efforts, models and model predictions should be archived for later use as test data for future debris modeling efforts. NASA and DoD could jointly lead these tasks.

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CHAPTER 6: MINIMIZING DEBRIS GENERATION

I. CURRENT ACTIVITIES AND RESEARCH

A. Design Philosophy

Although current hardware and ongoing activities have occasionally been modified for debris prevention, the design of many future systems now include debris-prevention objectives from the start. A good example of this is the design of the Space Station. Studies are looking at the proper method of disposal of used materials from the Station. One design option may be deorbiting used and waste material using a tether, rather than using the Shuttle. The objectives behind these studies are not only to prevent the creation of orbital debris, but also to protect the Station itself and to avoid contamination of the surrounding environment, thus inhibiting the scientific work on the Station.

B. Operational Procedures

Some operational procedures have already been adopted by various agencies to minimize debris generation. These procedures have occurred on an ad-hoc basis to date, but even this limited number of actions have already had an impact on the debris environment.

The first area in which debris-mitigation procedures have been incorporated is in mission operations, both for launch vehicles and for payloads. The previously-mentioned Delta upper stage modifications are a good example of this. The rate of increase of orbital debris from U.S. sources has dropped 15% because of this action alone. The disposal of spent rocket stages during flight has also been examined and in some cases altered for debris considerations. Launch planning is also affected by projections of the Collision Avoidance on Launch (COLA) program which warns of potential collisions or near misses for manned or man-capable vehicles before they are launched. Some launches have been momentarily delayed during their countdowns to avoid flying in close proximity of orbiting objects. However, it should be noted that sensor limitations affect the accuracy of any predictions. In addition, the Computation of Miss Between Orbits (COMBO) program projects proximity of payloads to debris objects soon after launch, and has been used on launches of manned missions.

Procedures affecting payloads include the use of the "disposal orbit" for satellites at the end of their functional lives. DoD, NOAA, INTELSAT, ESA and others have boosted aging satellites to altitudes above geosynchronous orbits, attempting to reduce the probabilities of debris-producing collisions in GEO and freeing up valuable GEO orbital slots. EVA (Extravehicular Activities) procedures will also be examined, and tighter control of tools and equipment during construction and operations will be necessary.

The second area in which debris-mitigating procedures have been adopted is in testing in space, primarily military-related testing necessary for our national defense. This testing is principally accomplished by means of mathematical modeling, but frequently must be performed in space prior to development decisions. Experience from DoD space experiments involving the creation of orbital debris has proved that we can minimize the accumulation of debris by careful planning. The Delta 180 SDI test was planned in such a way that nearly all of the debris generated by these tests re-entered within six months. This is because the test was conducted at low altitude to enhance orbital decay of the debris.

Predictions of the amount of debris and its orbital characteristics were made to assess range safety, debris orbit lifetimes, and potential interference with other space programs. The post-mission debris cloud was observed to verify predictions and to improve the break-up models. Such debris-minimizing test operations will now become standard procedure, consistent with test requirements. Another aspect of test debris-prevention is the use of debris-minimizing targets. An example is the development of a large instrumented balloon, rather than a solid structure, which can measure various aspects of an impact, without creating many thousands of small debris objects.

II. OPTIONS FOR IMPROVEMENT AND FUTURE RESEARCH

There are options available to control, limit, or reduce the growth of orbital debris. However, none of them can significantly modify the current debris environment; they can only influence the future environment. The three generic options of debris control are:

- Mitigating options, such as booster and payload design, preventing spontaneous explosions of rocket bodies and spacecraft, and "particle free" propellant research;

- Disposal or elimination of orbital debris objects; and

- Active removal or "cleaning" activities.

A. <u>Mitigation</u>

Launch vehicles and spacecraft often are designed so that they are "litter-free"; i.e., they dispose of separation devices, payload shrouds, and other expendable hardware (other than upper stage rocket bodies) at low enough altitude and velocity that they do not become orbital. This is more difficult to do when two spacecraft share a common launch vehicle. In addition, stage-to-stage separation devices and spacecraft protective devices such as lens covers and other potential debris can be kept captive to the stage or spacecraft with lanyards or other provisions to minimize debris, which is being done in some cases. These practices could be continued and expanded when possible.

The task of "litter free" operations could combine design and operational practices to achieve the goal of limiting further orbital debris created by any space operations. As a result of these efforts, the growth rate of orbital debris will decline, although the overall debris population will still increase.

When stages and spacecraft do not have the capability to deorbit, they need to be made as inert as feasible. Expelling all propellants and pressurants and assuring that batteries are protected from spontaneous explosion require modifications in either design or operational practices for both stages and spacecraft. For systems that have multi-burn (restart) capability, there are generally few, if any, design modifications required. For systems that do not have multi-burn capability, design modifications to expel propellants are more extensive. Detailed studies are required for implementation of these procedures in current systems (The Delta launch vehicle already includes such procedures).

Research could be conducted to develop "particle free" propellants. If successful, this technology research effort could eliminate the aluminum oxide particulates produced by current solid rocket motor propellants which add considerably to the small debris population. Such a program already exists for tactical missile propellant but there is no work currently being performed for space applications. A feasibility/demonstration program could be initiated to carry this out. The lead agency for this research effort could be DoD with NASA support.

B. <u>Disposal</u>

Disposal or deorbiting of spent upper stages or spacecraft is a more aggressive and effective strategy than merely inerting spent stages and spacecraft, since it removes from the environment significant mass that could become future debris.

For new spacecraft and launch systems, there is a large number of tradeoffs as to the physical and functional interface between the stage and spacecraft which can minimize the adverse effect of implementing a disposal requirement. Studies are required to assess the cost effectiveness of these tradeoffs, given a particular system and mission. DoD, NASA, and the private sector must each do these studies.

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For near term concerns, the highest priority for disposal must be given to high-use altitudes. However, disposal of debris at these altitudes is most costly and difficult.

There are two types of approaches that might be explored: mission design and system configuration and operations. Each needs to be applied to both LEO and GEO systems. Studies are required to assess the cost effectiveness of these options given a particular system and mission. DoD and NASA could lead these efforts and could solicit private sector involvement.

(1) <u>Mission Design</u> Some debris can be disposed of by careful mission design, but this may sometimes result in a significant performance penalty to both spacecraft and launch systems.

For some missions, the performance of the launch vehicle has sufficient margin that the stage has propellant available to do a deorbit burn. The stage needs to be modified to provide the mission life and guidance and control capabilities needed to do a controlled deorbit. Studies are necessary to define the mission duration needed and the procedures to be followed to control the stage disposal.

When the mission requires delivery of a spacecraft which itself has a maneuver capability, two alternatives are possible. One is to leave the upper stage attached for delivery of the spacecraft to orbit to maximize its maneuver capability, the second is to separate the spacecraft at suborbital velocity so that the stage decays naturally, and the spacecraft uses its onboard propulsion to establish its orbit. From a cost-penalty perspective, alternative one results in a greater mass in orbit, a potential debris hazard, while alternative two increases the complexity of the spacecraft. Assessing which alternative is more appropriate requires further study.

An alternative to entry and ocean disposal is relocation to a "trash" orbit. In LEO, this is generally not an advantageous strategy because it generally requires a two-burn maneuver that is more fuel costly than the single burn for entry. In any case, it is not certain that any LEO orbit should be used for "trash". However, "trash" orbits in LEO are used for nuclear payloads due to reentry environmental and safety considerations. Systematic studies to determine what is the most cost-effective course of action, and what considerations dictate the optimization criteria for a particular project are required.

For GEO missions, the pertinent considerations for disposal are the launch date and azimuth and the perigee of the transfer stage. For multiburn systems, positive ocean disposal can be achieved with an apogee burn of a few meters/second if the stage has sufficient battery lifetime and contains an attitude reference and control system.

In addition, there is a set of launch times to GEO which so align the orbit of the transfer stage that natural forces, e.g., Sun, moon, earth properties etc., act to lower or raise the perigee of the stage. Consideration of the effect of these forces can minimize the cost of active control of liquid propellant stages and is a low cost technique for the disposal of solid rocket motor stages. The only alternative strategy for the disposal of solid rocket motors is to orient the thrust vector of the rocket in a direction so that the perigee of the transfer orbit resulting from the burn is at a low enough altitude to cause the stage eventually to reenter (sometimes referred to as an "off-axis burn"). This strategy results in about a 15% performance penalty for the stage. As is the case for the LEO stages, comprehensive studies are needed to determine the details of the procedures required and which approach is most cost effective for any given project.

Use of "disposal" orbits is a technically feasible strategy for clearing the geostationary orbit region but is not the only available strategy. The cost-effectiveness of a disposal orbit strategy compared with other strategies has not been examined. If raising the orbit is to be the technique of choice, then it requires planning and reserving the necessary propellant resources to effect the maneuver. Preliminary studies indicate that the orbit needs to be raised on the order of 200 km to serve the intended purpose, not the 40 - 70 km that has been used by some operators. The necessary propellant for this maneuver might be equivalent to a year's station-keeping capability and a potential loss of revenue, for example, estimated to be in excess of $20 million for an INTELSAT VI spacecraft.

Finally, beyond 25,000 km, it is less costly to go to an escape trajectory from earth orbit, rather than deorbiting, because the fuel required to reenter from a circular orbit is a function of altitude.

(2) <u>System Configuration and Operations Studies</u> Mission design appears to be the least cost option for disposal. However, systems not designed with a disposal requirement have other alternatives available, such as design modifications to current systems or design attributes for new systems.

For LEO stages or spacecraft, it may be feasible to maneuver to lower the perigee and employ some device to significantly increase drag. A drag device, such as a large balloon inflated by a subliming agent, could have a lower overall performance penalty in both mass and complexity than using only spacecraft propulsion for disposal.

In geosynchronous transfer stages, the design and operation timeline could be modified so that the separation and avoidance maneuver could provide the velocity increment to cause the stage to enter. Drag devices may also increase accuracy of the predictions of atmosphere entry points.

In the mission design studies noted above, preliminary surveys of the concepts have been conducted. However, systematic studies and cost effectiveness assessments are also required. DoD and NASA could be the lead agencies for these studies.

C. Removal

Removal is the elimination of space objects by another system. At present there is no capability nor perceived need for removal at GEO, so this discussion pertains only to LEO. Removal options may also raise significant international legal issues, which are discussed in Chapter 9, Legal Issues.

1. <u>Large Objects</u> The removal of large, inert objects requires an active maneuver vehicle with the capability to rendezvous with and grapple an inert, tumbling and non-cooperative target; and the ability to properly and accurately apply the required velocity increment to move the object to a desired orbit. These capabilities have been demonstrated by the Space Shuttle, but no unmanned system has these capabilities for higher altitudes and inclinations. There have been a few conceptual studies; however, detailed design and operations analyses, development, and demonstrations could be conducted. See Appendix 3 for private sector related proposals. NASA could lead this effort.

The design, development and operation of a maneuverable stage to remove other stages and spacecraft requires a high degree of automation in the rendezvous, grapple, and entry burn management if cost of operations are to be kept reasonable. The long and short range systems to acquire, assess the orientation, grapple, secure, determine the center of mass, and plan the duration and timing of the entry burn all require development and demonstration. The component technologies require study and analysis, followed by breadboard and prototype development. With some preliminary efforts already underway, NASA could assume lead agency responsibilities.

(2) <u>Small Objects</u> The multiplicity of small objects makes it impossible to actively acquire and enter each object individually. There are two classes of schemes that have been proposed for the removal of such debris. One is the use of active or passive devices to intercept particles with a medium, such as a large foam balloon, which absorbs kinetic energy from the particles. This causes the objects' perigee to fall to

regions where aerodynamic drag induces entry. The other is an active device which illuminates the particle with a beam of directed energy, causing the particle either to lose velocity or to be dissipated into fragments that are no longer of significant mass. See Appendix 3 for private sector proposals.

Since the intercept balloon does not discriminate between debris and functioning spacecraft, it could inflict damage on usable assets. Avoidance of such damage might require active maneuvers by the intercept balloon. The advantages of a simple system could be lost if the system's operation becomes too complicated.

The active directed energy system requires elements that do not yet exist. This system requires high energy output, high precision pointing, and instruments for debris object detection and beam aiming so the intercept can be accomplished, without accidentally harming other operational spacecraft.

Studies are required to determine which is the preferable system to implement. The development of the detection and aiming instruments have a great deal in common with similar detectors required for the environmental monitoring task described above and the collision avoidance task described below. These activities could be led by NASA and DoD.

CHAPTER 7: SURVIVING THE DEBRIS ENVIRONMENT

I. CURRENT ACTIVITIES AND RESEARCH

The need for protection from orbital debris is influencing the design of new spacecraft. In the past, spacecraft design took into account the natural meteoroid environment. However, all future spacecraft will also have to consider man-made debris hazards during design. The Space Station is only the first to do so.

Missions can also be planned from the outset to avoid debris-threatening situations. For example, congested orbital inclinations or altitudes could be avoided, consistent with mission objectives. This already takes place in interplanetary missions in which hazards from the naturally occurring asteroid belt are avoided. Proper treatment of disposable components can also be part of mission planning. For example, NOAA has begun requiring that some of the hardware involved in upper stage separation be kept attached to the upper stage rather than float away as separate debris objects.

II. OPPORTUNITIES FOR IMPROVEMENT AND FUTURE RESEARCH

A. Mission Design

Spacecraft and launch systems can be designed and operated in ways that reduce their vulnerability to the debris environment. The acceptability of any given vulnerability reducing strategy is a function of the mission objective of the space system. Mission design is an option for using current systems in alternative ways. Orbit selection to avoid regions of high probability of debris collision is feasible for some spacecraft missions but not practical for others without significant mission-objective compromise. For example, the same observations made from different orbits might require different instruments of varying cost and complexity. DoD, NASA, and private companies each need to assess the cost of such a strategy.

B. System Protection

Spacecraft can be protected from serious damage by using shielding or by designing the spacecraft to be damage-tolerant (i.e., redundant systems and critical sub-systems separation to prevent single event catastrophes). The most straight-forward approach is shielding. Although shielding against micro-meteorites has always been a consideration, the existing and anticipated levels of threat from orbital debris makes shielding more important. In addition, much of the man-made debris falls into larger size categories than naturally occurring debris. This somewhat larger debris, in the millimeter (0.1 cm) to centimeter range, potentially calls for different types of shielding than have been used in the past. The method of shielding to be used can significantly affect the design of spacecraft, in configuration, performance, and cost, and must be part of the design philosophy from the outset.

Shielding can be an integral part of the spacecraft, such as a protective outer shell, or can be used as a movable shield. See Appendix 3 for private sector proposal. In most cases, integral shielding could be used to protect against smaller debris, which would be damaging but not destructive. A more robust shield could be used for less frequent but more destructive debris or to provide local temporary shielding, such as for astronauts during EVA or to protect a sensitive payload. The threshold between damaging and destructive impacts would be mission dependent.

Designs for survivability of the spacecraft if and when an anticipated collision occurs are becoming more explicit. One option is a system of active louvers or shutters that could be maneuvered to protect delicate equipment in the event of a collision. A similar idea utilizes a "turtle shell" spacecraft concept. This type of spacecraft could consist of a main protective structure with ports through which sensors and arrays could be deployed and later withdrawn into the protective structure in the event of an anticipated collision. Shielding of sensitive elements of a satellite, such as mirrors and lenses, when not in use is a semi-active technique that is effective against small to medium debris and is currently used in the MIR space station.

A form of shielding is based on a principle developed by the English astronomer Fred Whipple involving multi-wall fabrication in which the exterior wall serves as a sacrificial barrier. This breaks up impacting debris and disperses approximately 80% of the fragmented debris over a larger area on the interior wall. The remaining 20% is deflected away from the shield, but is too small to constitute a hazard. This is the baseline shielding approach being studied to protect the Space Station modules.

Some far-term research proposals offer a high-payoff potential. There are five distinct areas for shielding research. Both DoD and NASA have on-going programs which are mutually beneficial. Both programs deserve continued support and increased cross-fertilization.

(1) <u>Hypervelocity impact testing and facilities</u> Proposed research includes development of a larger, more durable gun facility with the capability of firing 2-cm projectiles weighing 10-15 grams at speeds up to 12 km/sec. Test methods might also be developed for qualifying new materials and shielding concepts

as well as validating hypervelocity impact analysis methods. DoD has conducted research in this area, and close coordination between NASA and DoD should be continued.

(2) Modeling impact effects Research is recommended to develop advanced methods for accurately and efficiently predicting the response of materials and structures to impact, including internal shock wave propagation; material phase change and rejection; and deformation and penetration. Particular attention could be directed to non-homogeneous materials, such as composites, and to modeling methods more advanced than classical hydrodynamic approaches. Also, modeling effects on complete spacecraft, in addition to discrete sections, needs development.

(3) Materials research and development This activity could concentrate on advanced lightweight materials system including fiber and particulate composites and layered materials. Materials could also be examined which would pulverize upon impact rather than fragment, creating less hazardous debris.

(4) Shielding concepts This research area could develop structural shielding concepts for both fixed, integral shielding and movable shields. The emphasis could be placed on light weight, low cost and the capture of collision products. A major goal might be to develop effective shielding concepts for debris up to 2-cm in size (approx. 10-15 grams) with speeds up to 12 km/sec.

(5) Validation and certification This research area could involve all four previous areas and develop analytical and test methods for qualifying the survivability of entire spacecraft.

Closely related to survivability is the concept of redundancy. This concept has historically been used to compensate for possible electronic component failure. However, it has definite benefits in the event of a minor collision with debris which might damage one or more instruments or components onboard the spacecraft. With redundant systems physically separated on the spacecraft, it may be able to continue functioning.

The ultimate objective of the above research projects could be to develop methods to configure a spacecraft to minimize the damage from debris impact. This will involve assessing the response of a spacecraft to a penetrating impact and to predict the extent of internal damage. Automated design methods could then be developed to trade off the benefits from shielding, configuration and redundancy in an optimal manner based on mission costs and requirements.

Protecting a satellite from debris requires significant investment by the owner/operator. The best current protection is shielding. There will be development costs to create increased shielding. For passive shielding, the weight will translate to added dollars and less payload. If the shielding is active (can move into place as necessary), there are command and control issues and added complexity, though weight can probably be saved.

C. <u>Collision Avoidance</u>

The concept of active collision avoidance is in a very early stage of definition, and studies of all the concepts in this section are needed to define their feasibility. It should be noted that there are extremely difficult problems (cost, weight, technology) associated with active collision avoidance methods.

Active collision avoidance of all space objects is not currently practiced, nor is it likely to become feasible in the near-term. However, there are specific cases and orbits where collision avoidance is practiced to a limited extent. Utilization of COLA and COMBO programs was discussed earlier. In addition, collision avoidance in the geosynchronous region has been practiced on a routine basis by DoD since 1982.

The major deficiency with all of these activities is the error in the tracking accuracy. Current tracking accuracy is not sufficient to permit a collision avoidance maneuver to be made. Often it is just as likely to maneuver into the path of an oncoming object as away from it due to the tracking inaccuracies. In the geosynchronous orbit, if close approaches repeatedly occur, one satellite may be maneuvered. For one time close approaches, usually no maneuver is performed.

The maneuvering of a satellite to avoid a collision obviously requires the provision of a maneuver capability on the satellite, with associated mass and cost penalties. Studies are needed to understand the tradeoffs involved in implementing this capability. For example, rapid maneuvers require significant propulsion capability and fuel. Precise prediction and timely notice allow smaller, less costly maneuvers. While some measure of collision avoidance is feasible, it is very costly and, for most systems, not practical.

In addition, the threatened satellite must receive warning of a potential collision. Currently, the warning can only be provided by the existing Space Surveillance Network (SSN). There are several limitations to the existing SSN for collision avoidance. The first is lack of accuracy, which is currently inadequate to support collision avoidance maneuvers. A second important SSN issue is sensitivity. As stated earlier in this report, the minimum size object that can be reliably detected in LEO is about 10 cm in diameter, yet avoidance of particles of 1 cm diameter is desirable. This could require an increase in sensitivity of a factor of 100, requiring a major redesign of most sensors. The increased sensitivity could result in a large increase in the number of objects maintained in the catalog, resulting in a corresponding increase in required computational resources needed.

On-board detection and computation can sense and respond to debris too small to be tracked from ground facilities but its effectiveness is limited by constraints on the on-board sensors' field of view. This means that it can see threats several revolutions ahead in plane but may have only seconds to react to out of plane threats. On-board computation needs would be significant both in technological capabilities and payload tradeoffs.

An onboard radar intended to detect the debris in all directions around the spacecraft would require excessive power. Consequently, a space-based radar intended primarily to monitor the total environment around the spacecraft does not appear promising.

For a longer-term solution, it may be desirable to develop an autonomous collision avoidance sensor, possibly a combination of a wide-angle infra-red telescope and a narrow beam radar, to be carried on very large satellites
hod to remove debris threat may be to pulverize the debris. For any method of removing the threat to be effective, the debris must be pulverized into pieces less than 0.01 cm. diameter and/or have all relative velocity removed.

A final possibility is repulsion of the encroaching debris by some force field. This may indeed be possible for small debris, which often acquires a significant charge; but the power requirements for such a system would probably be prohibitive. For medium to large debris there is no known repulsive force that would be effective.

PART THREE: INTERNATIONAL EFFORTS, LEGAL ISSUES AND COMMERCIAL REGULATION

CHAPTER 8: INTERNATIONAL IMPLICATIONS AND RECOMMENDATIONS

I. APPROACHES TO OTHER GOVERNMENTS

The United States cannot address the debris issue alone without the cooperation of other governments. Several other nations and organizations (ESA, Arianespace, INTELSAT, INMARSAT) have contributed to the debris environment through their space activities. The Soviet Union has become the largest generator of new space debris, and the most significant recent debris incident was the explosion of an Ariane upper stage. Responsibility for space debris also extends to all nations and organizations that operate launchers and satellites, and includes "the customers" of activities conducted in space -- such as telecommunications. Clearly, at some point, we will need to approach foreign governments and organizations to seek their cooperation. The substance, timing, modalities, and venue of such an approach will have to take into account other findings of this study.

Informal discussions of various aspects of the orbital debris issue have already taken place among space agency scientists, engineers and managers. These discussions have occurred at technical society meetings and in occasional agency-level meetings.

NASA and ESA have held technical discussions about the redesign of Ariane third stages, which were exploding in orbit similar to NASA's earlier experience with the Delta upper stages. ESA has since redesigned the third stage to vent propellants and pressurants to prevent those explosions. The first launch of the fully modified third stage is scheduled to take place in May 1989.

Similar exchanges on upper stage design and experience have taken place between NASA engineers and their counterparts at the Japanese space operations agency, NASDA. Subsequently, the upper stage of the H-1 launch vehicle has been modified. Chinese space personnel have also made inquiries to NASA personnel about debris matters, as have Soviet scientists.

ESA has established an Orbital Debris Working Group to produce a study of the current debris environment and to make recommendations about how ESA should deal with the issue. This Working Group has recommended that ESA create an orbital Debris Investigation Program, complete with appropriate funding and staff. Among other recommendations is a proposal to coordinate all debris activities and research in Europe through the ESA program. ESA's Director General is expected to act on these recommendations in the near future.

Annual coordination meetings between the NASA Orbital Debris Steering Group and the ESA Working Group have taken place since 1987. The meetings have focused on discussions of ongoing activities, of research and modeling, and of potential areas of technical cooperation. A recent fallout from these discussions has been the development of an arrangement to share debris tracking data. Other potential cooperative activities include modeling activities and hypervelocity testing.

Several foreign governments and international organizations have taken steps to address the disposition of geosynchronous satellites at the end of life. INTELSAT, Telesat (Canada), INMARSAT, Eutelsat, and ISRO (India) have all adopted policies requiring their future satellites to have orbit-raising capabilities at the end of life. INTELSAT and Telesat have already boosted satellites out of GEO. Other countries, such as the Soviet Union, Japan, and Italy, although they have not announced formal policies, have also boosted satellites. However, it is not clear that these actions have been sufficient to avoid increasing the debris accumulation in GEO.

II. TACTICAL CONSIDERATIONS

In possible future approaches to other Governments, one of our goals will be to ensure that the United States' commercial space industry is not significantly disadvantaged by taking policy, regulatory, or technical steps that are not followed by our competitors. We also do not want to constrain disproportionately our civil or military space programs, or drive our launch or satellite industries offshore to escape U.S. regulations. Consistency of policies, standards, and practices among nations active in space is obviously the ultimate objective. On the other hand, we cannot wait for a solution agreed to by most or all of the players before we act.

In examining options for an approach, we will need to address its scope, its level, its timing, and its content. Options for the <u>scope</u> of the approach include: bilateral - space powers only; bilateral - all nations; multilateral - space powers only; multilateral - all nations.

In the longer term, additional nations will become launching and satellite operating states. In addition to nations such as India and Brazil which already are developing launch vehicles and satellites, there are several threshold countries attempting to build their own launch vehicles, such as Pakistan and Argentina. In addition, there are nations that intend to build or purchase satellites which would be launched on the vehicles of others. As satellites also can become debris or contribute to it, the cooperation of manufacturing, purchasing, and operating states will be necessary.

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As for bilateral versus multilateral approaches, bilateral approaches would be more manageable; the only existing multilateral body which deals with general space issues at the government level is the U.N. Committee on the Peaceful Uses of Outer Space, where legal and technical issues have become heavily politicized. ESA is a multilateral body but they conduct a unified spacecraft and launch program and can be dealt with on a bilateral basis. Attempts have been made in the International Telecommunications Union (ITU) to regulate debris generation in GEO but the issue is still under study.

As for the level of our approaches, both government level and agency level approaches are necessary. Initial agency-to-agency approaches are useful for the exchange of information, and for exchanges of views on technical options and impacts on specific programs. However, discussions that involve potentially sensitive national security-related information will require DoD participation. Additionally, whenever the intent of discussions is to lead eventually to formal policy agreement, or whenever a previously technical discussion turns toward such an intent, the discussions should be conducted by a U.S. interagency team (including NASA, DoD, State, DOT, DOC, and other agencies as appropriate). Government-to-government approaches will be necessary to convey our level of concern at the political level and to establish a political context for the discussion of the issue. It will be important for all of these approaches to be coordinated.

The timing of our approaches will be affected both by our own state of progress on the debris issue and by external events, such as a major debris incident or the raising of the issue in a multilateral body. Clearly, internal U.S. government agreement is essential on at least the general substance of U.S. policy on the issue before we make broad policy proposals to other governments. However, there could be phases in the timing of our approaches. For example, we may be able to begin exchanging information about space debris with other governments early in the process.

From a foreign policy point of view, simply informing other governments of our own declared policy and the interagency study can only serve as a first step. We must also offer to begin a dialogue in which information about space debris would be exchanged. Next steps could be to seek agreement with our broad policy statement, and to seek agreement on specific proposals for technical and regulatory measures. At that stage, we will want to seek the agreement of foreign governments to our approach to private sector operators, so that the U.S. private sector is not disadvantaged in relation to its foreign competitors.

In addition to technical and operational considerations, an important question is the role of international space law and regulation. Some aspects of international law, particularly liability, have implications for space debris. An issue to consider is whether we want to expand upon existing multilateral agreements, pursue a separate additional agreement on space debris, or simply seek the harmonization of laws, regulations, and practices by space powers and organizations operating space systems.

III. INSTRUCTIONS TO DELEGATES

The space debris issue has been raised by other nations in meetings of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), the U.N. Conference on Disarmament, the International Telecommunications Satellite Organization, and constituent bodies of the International Telecommunication Union. In the latter case, a specific proposal for the removal of satellites from the geosynchronous orbit is under review. On July 15, the U.N. Secretariat asked the U.S. to provide information on space debris by December 26, in the context of a working group on nuclear power sources in space.

INTELSAT and INMARSAT operate satellite systems and are users of launch services whose operations and whose members could be affected by national debris policies.

(Appendix 2, [classified Confidential] outlines recommended approaches to other governments and international organizations.)

Chapter 9: Legal Issues

I. THE MEANING OF "SPACE DEBRIS"

"Space debris" is a popular rather than legal term. As such, it does not have a precise definition. The popular term is commonly used to indicate components or fragments of space objects that are spent or no longer functional. Space debris usually refers only to tangible, physical objects that are man-made (and not, for example, meteorites). Legal sources that are potentially relevant to space debris do not use the term "space debris". Rather, they use terms such as "harmful interference" or "component parts of a space object". Thus, legal terms must be analyzed on a case-by-case basis to determine whether they could include the popular notion of "space debris".

II. APPLICABLE DOMESTIC LAW

There are two kinds of domestic law that are potentially applicable to space debris, regulatory law concerning standards that must be met before launch and tort law relating to damage that occurs as a result of space debris.

With respect to regulatory law, U.S. governmental space activities (both civil and military) do not appear to be governed by explicit legal standards regarding space debris. Several U.S.Government agencies consider that, as a legal matter, the National Environmental Policy Act (NEPA), which requires an environmental assessment for certain federal actions that may affect the environment with the United States, and E.O. 12114 for certain federal actions that may affect the environment of the "global commons outside the jurisdiction of any nation (e.g., the oceans or Antarctica)", do not apply to space. These agencies have therefore concluded that an environmental assessment of the potential generation of space debris on orbit is not required. Some agencies have nevertheless conducted such an assessment as a policy matter.

Regarding private commercial launches, the Commercial Space Launch Act gives authority to the Department of Transportation to prescribe such requirements, with respect to launches and the operation of launch sites, "as are necessary to protect the public health and safety, safety of property, and national security interests and foreign policy interests of the United States" (49 U.S.C. 2607(b)). Although the Secretary of DOT has not used this authority to issue regulations setting forth standards for the minimization of space debris by the commercial launch industry, this provision could be so invoked.

With respect to remote sensing from satellites, the Land Remote Sensing Commercialization Act of 1984 provides that a licensee shall "upon termination of operations under the license, make disposition of any satellites in space in a manner satisfactory to the President" (section 402(b)(3)). This provision would appear to permit the Department of Commerce to require that a spent spacecraft not be left in a position that contributes to the proliferation of space debris. Presumably, design and orbital conditions could be imposed to promote the desired disposition.

With respect to the second kind of applicable law, it is possible that U.S. tort law could potentially be applied in the case of damage caused by space debris in the United States. (A suit against the United States, as opposed to a private entity, would have to be in accordance with the Federal Tort Claims Act.) U.S. courts might also establish jurisdiction where negligence or a wrongful act in the United States resulted in damage caused by debris in space or elsewhere outside the United States. Thus, even absent federal regulation, the development of a body of common law related to damage caused by space debris could lead to the existence of standards regarding the minimization of such debris.

III. <u>APPLICABLE INTERNATIONAL LAW</u>

There are several international agreements potentially bearing on space debris. The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, which entered into force on October 10, 1967, contains principles which, although general, would appear relevant to any discussion of space debris. First, the Treaty provides that parties bear responsibility for "national activities" in space and that non-governmental activities require authorization and continuing supervision (see Article VI). This provision makes clear that a party must have some kind of approval/monitoring process for private space activities and that, although the scope of "national activities" is unclear, a party could be responsible for at least certain of its nationals' activities in space.

Second, the Treaty provides that parties are obliged to conduct all their outer space activities with due regard to the corresponding interests of other parties (see Article IX). Although parties are called upon to avoid adverse changes in the environment of the Earth resulting from the introduction of "extraterrestrial matter", it is unlikely that this clause was intended to cover matter originating on Earth.) In addition, a party is obligated to consult if an activity planned by it or its nationals would cause "potentially harmful interference" with activities of other parties in the exploration and use of outer space. It would appear that the generation of space debris could, depending on the circumstances, be viewed as falling within the scope of this provision.

Third, the Treaty provides that each party that launches or procures the launch of a space object, as well as each party from whose territory an object is launched, is internationally liable for damage to another party (or its natural/juridical persons) by such object (or its component parts) on the Earth, in air space, or in outer space. This principle is further elaborated in the Liability Convention, as discussed below.

Fourth, the Treaty provides that the party on whose registry a space object is launched into outer space retains jurisdiction and control over such object while it is in outer space (Article VIII). The ownership of a space object and its component parts is not affected by their presence in outer space or their return to Earth. These principles are relevant to the issue of destruction or removal of non-U.S. debris, as discussed below.

The treaty that is perhaps most relevant to a discussion of space debris is the Convention on International Liability for Damage Caused by Space Objects, which entered into force on September 1, 1972. The Convention imposes upon a launching State absolute liability for damage caused by its space object on the Earth or to aircraft in flight; in the case of damage other than on the Earth to a space object by the space object of another State, the latter is liable if the damage is due to its fault or the fault of persons for whom it is responsible. A "space object" is defined to include "component parts of a space object as well as its launch vehicle and parts thereof"; there is no requirement that such parts be functional. Thus, as space debris, and a launching state's potential liability under the Convention would continue despite the non-functional nature of its space object.

The present state of space technology does not permit activities in space that are completely debris-free. The question therefore arises whether it would be necessary, in order to establish "fault" for damage caused by debris in space, to demonstrate more than the mere production of debris as a consequence of legitimate space operations. It would appear that other factors such as the proximity of other space objects, the reason for the creation of the debris, and the probability of causing interference with the space activities of other nations must be considered when establishing "fault".

Under the Convention, joint launching states are jointly and severally liable for damage; as between themselves, they may apportion such liability, but a third state may seek full recovery from either of them. (A "launching State" means a state that launches or procures the launch of a space object, as well as a state from whose territory of facility a space object is launched.) A party that suffers damage or whose natural or juridical persons suffer damage may bring a claim through diplomatic channels. The standard of compensation is to be in accordance with international law and principles of justice and equity, in order to restore the injured party to its pre-damage condition. In the absence of a diplomatic settlement, the Convention provides for the establishment of a Claims Commission at the request of either party. The Commission's award is only binding if the parties so agree; otherwise, it is a recommendatory award that the parties are to consider in good faith.

Although the Liability Convention provides a legal mechanism for establishing liability and damages, there would likely be problems of proof associated with a claim based on damage caused by space debris. In the likely event that damage to or destruction of a space object was caused by a small, unobservable fragment, it would be difficult to establish the identity of the launching state and therefore to invoke the Liability Convention.

The Convention on Registration of Objects Launched into Outer Space, which entered into force on September 15, 1976, requires the registration with the United Nations of any space object launched into earth orbit or beyond. If there are two or more launching states, those states must determine which of them will register the space object. In the event that a piece of space debris caused damage, this registration system might assist the state suffering damage in identifying the launching state (or at least one of two or more joint launching states) associated with such debris. If the damaged state were unable to identify the debris which caused the damage through the UN registration system, other parties (in particular those possessing space monitoring and tracking facilities) would be called upon under the Convention to respond to the greatest extent feasible to a request from that state for assistance in the identification of the debris.

The Agreement on the Rescue on Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space, which entered into force on December 3, 1968, also contains provision potentially relevant to space debris. Under this Agreement, a party discovering that a space object or component part thereof has returned to Earth in its territory is obligated to notify both the launching state and the United Nations. If the discovering party has reason to believe that the object or part is of a "hazardous or deleterious nature", that party may notify the launching state, which is to take immediate, effective steps (under the direction and control of the discovery party) to eliminate possible danger of harm.

In terms of radioactive space debris, there appear to be three relevant international agreements. The Limited Test Ban Treaty, which entered into force on October 10, 1963, obligates parties to prohibit, prevent, and not carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control in, inter alia, outer space and the atmosphere. The Treaty was intended to prevent the wide-ranging distribution of radioactive debris.

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The Convention on Early Notification of a Nuclear Accident, which the United States is expected to soon ratify, requires parties to notify potentially affected states in case of an accident involving nuclear reactors in space, or the use of radioisotopes for power generation in space objects, from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another state.

The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, to which the United States will also shortly adhere, establishes a framework under which a party may provide assistance to another party in the event of a nuclear accident or radiological emergency, which could include the presence of radioactive space debris.

The destruction or removal (retrieval or deorbit) of non-U.S. debris from outer space would raise a number of issues under international law. As mentioned above, under Article VIII of the Outer Space Treaty, the State of registry retains jurisdiction and control over a space object while it is in outer space, and ownership of objects and their component parts is not affected by their presence in space. Ownership would also not be affected by the loss of function of the space object. If the launching State consented to the destruction or removal of its space debris, or if it abandoned its rights to the debris through a clear expression of intent, destruction or removal could be considered lawful. However, under customary international law, State property remains State property unless expressly relinquished. (Under maritime law, for example, the United States has consistently maintained that sunken State ships remain the property of the flag State until title is expressly transferred or abandoned, and that abandonment cannot be implied from the absence, even over a long period of time, of acts evidencing an interest in such property.)

In order to take destruction or removal measures in the absence of consent or abandonment by the launching State, it would appear that an argument would have to be made that the jurisdiction and ownership rights of the launching State must be balanced against Article IX of the Outer Space Treaty, which, as noted above, requires States to conduct their space activities with due regard to the corresponding interests of other parties. Although a launching state is not legally required to remove its objects from space (i.e., the presence of space debris is not prohibited), if debris were adversely affecting the activities of other space users, an argument could be made that a State may lawfully take appropriate measures to protect itself from harm. See Appendix 3 regarding private sector interest in legalizing salvage operations.

CHAPTER 10: COMMERCIAL REGULATION

INTRODUCTION

In order to understand how government regulation will play a role in the commercial space sector's debris reduction effort, it is necessary to understand the Federal regulatory approach to the commercial sector as well as the different types of regulation. Following an overview of regulatory authority, this chapter will outline a basic approach for integrating commercial regulation with other debris mitigation efforts.

I. REGULATORY OVERVIEW

The Regulatory Program of the U.S. Government* identifies three principal functions of Federal regulations: (a) the direct control of commerce and trade, i.e. traditional "economic" regulation; (b) the protection of public health and safety and the environment; and (c) the proper management and control of Federal funds and Federal property. The functions and authority of the three principal Federal agencies involved in the regulation of commercial space activities--i.e. the Department of Transportation (DOT), the Federal Communications Commission (FCC) and the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA)--fall into all three categories of regulatory functions. The authority of both the FCC and NOAA concerns the first category: the regulation of business activities principally for economic reasons. In contrast, DOT and the FCC are charged by statute with carrying out the second category of functions: DOT regulates the commercial launch sector to protect public health and safety, as well as other public interests, and the FCC regulates communications by wire and radio for the purpose of promoting safety of life and property. The FCC's authority also falls into the third category in that it manages and controls the private sector's use of a federal property (the national radio frequency spectrum).

The Communications Act of 1934 confers on the FCC the authority to regulate interstate and foreign commerce in communications by wire and radio. The FCC's authority includes the responsibility for allocating a finite number of available radio frequencies and managing their use. The FCC's role in regulating commercial space activities derives from this authority and involves licensing providers of telecommunications services (which may include satellites), assignment of orbital positions consistent with international treaties and establishment of standards governing transmitter design and operation to ensure appropriate frequency usage (such as

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* Regulatory Program of the U.S. Government, Executive Office of the President, Office of Management and Budget, April 1, 1985 - March 31, 1986, at page xiv.

spacecraft control pointing accuracy and position tolerance). To carry out these responsibilities, the FCC authorizes the construction, launch and operation of U.S. commercial communication satellites in order to maintain the communications capability of the radio frequency spectrum and geo-stationary satellite orbit, while at the same time recognizing DOT's responsibility for safety issues associated with payload launch and mission.

NOAA's authority with respect to commercial space activities is granted under Title IV of the Land Remote-Sensing Commercialization Act of 1984. NOAA is responsible for licensing private remote-sensing space systems for the purpose of providing a framework for the phased commercialization of land remote sensing while maintaining U.S. leadership in civil remote sensing, assuring continuous data availability to the Federal Government and fulfilling U.S. international defense and security commitments. Licenses may be issued for systems utilizing a civilian U.S. Government satellite or vehicle as a platform for the system, as well as privately-owned satellites. Section 402(b)(3) of Title IV requires all licenses to include a condition under which the licensee must "upon termination of operations under the license, make disposition of any satellites in space in a manner satisfactory to the President." This clearly provides adequate authority to require that a spent spacecraft not be left in a position that contributes to the space debris problem. Presumably, any reasonable combination of design and orbital conditions could be imposed to promote the desired disposition. By implication, authority to control the disposition of the entire spacecraft would include authority to impose reasonable conditions directed at maintaining a spacecraft intact during operations (i.e., in orbit) or at controlling the disposition of any pieces shed during operations. NOAA's authority under Title IV does not extend to activities that are part of the launch.

The principal purpose of the authority granted to the Secretary of Transportation under the Commercial Space Launch Act of 1984 is to oversee and coordinate the conduct of commercial space launch operations in a manner that protects the important national interests associated with such activities: public health and safety, safety of property and U.S. national security and foreign policy interests. The Secretary is empowered to issue licenses authorizing the conduct of commercial launch activities and to establish the regulatory regime for ensuring that they are conducted safely and responsibly. In the course of devising appropriate regulatory guidance the Secretary may, by regulation, eliminate any existing Federal requirements otherwise applicable to commercial launch activities that is determined to be unnecessary to protect the national interests. The Secretary may also add new requirements to safeguard those interests or to ensure compliance with U.S. international obligations. DOT's charter as a safety regulatory agency encompasses all non-government launches conducted by U.S. citizens or from U.S. territory; payloads involved in launches subject to DOT licensing requirements; and non-U.S. Government launch sites (e.g. privately-operated or state-run spaceports). With specific regard to non-government payloads, proposals to launch payloads that are not subject to licensing by another U.S. Government agency--such as reentry vehicles, foreign-owned telecommunications and land remote-sensing satellites, materials processing payloads and other innovative space applications--must be [[reviewed]] by DOT from the standpoint of the national interests the Department is charged with protecting. If any such proposal runs counter to those interests, the DOT can prohibit the launch of the payload in question.

DOT's authority over satellites is very broad except with respect to two specific areas: (a) the licensing and regulation of telecommunications satellites by the FCC under the Communications Act of 1934; and (b) the licensing of remote-sensing space systems by NOAA under the Land Remote-Sensing Commercialization Act of 1984. To the extent that a payload requires a license under either of these regimes in order to be launched, DOT may not duplicate the review process of either of those agencies or reconsider the merits of the specific service to be provided pursuant to the license. Although a separate licensing procedure exists for these two types of satellites, DOT's authority to ensure the safety of commercial launch and payload operations--including the safety of the pre-launch, launch and in-space transportation phases of these operations--is nevertheless unaffected.

The uncontrolled proliferation of orbital debris poses a threat to public safety, the safety of property and U.S. commitments on international liability issues. Federal regulation of the commercial space launch sector for the purpose of preventing and controlling orbital debris, therefore, falls into the "safety" category of regulatory functions. As noted above, DOT is expressly authorized to regulate commercial launch activities in terms of public safety and other public interests, and the FCC is expressly authorized to regulate the use of radio to promote the safety of life and property. In addition, the relationship among the regulatory agencies for space purposes can follow the existing alignment for terrestrial activities. For example, whereas the FCC regulates mobile land, marine or airborne radio communications systems and service, DOT regulates the vehicle (e.g. truck, ship or aircraft) by which the service is provided. In addition, similar to the way in which the FCC regulates the painting of radio towers consistent with FAA air navigation requirements, the FCC's regulations may include physical movement of spacecraft to promote safety of life and property according to DOT standards. As to space-related activities, therefore, the economic focus of NOAA and the regulatory focus of the FCC on the provision of telecommunication services would continue to be distinguished from DOT's focus on the safety and transportation components of the launch vehicles and spacecraft.

II. DEPARTMENT OF TRANSPORTATION APPROACH

By virtue of its statutory authority and responsibilities, DOT has assumed a comprehensive approach to on-orbit safety and space debris issues. Implementation of this approach includes on-going regulatory action and current research programs, as well as plans for additional activity to address the orbital debris problem, in the following areas: (a) licensing and enforcement; (b) safety and regulatory research and standards development; and (c) financial responsibility/insurance requirements and risk allocation regimes.

A. Licensing and Enforcement

DOT is already working with the commercial launch companies, through the licensing process, to address the orbital debris issues raised by proposed commercial launch activities.

The launch license application review process consists of two components, a Safety Review and a Mission Review, which address orbital safety and, by implication, debris control and prevention in the following manner.

- Review of ELV staging and maneuvering hardware reliability and safety, including statistics on previous failures, the failure mode and effect analysis (FMEA) and consequences of such failures;

- Review of mission planning and design, including the proposed orbital trajectory, the orbital insertion and separation maneuvers and estimated orbital life for proposed geo-transfer and parking orbits;

- Review of the license application to ensure that the operational plans preserve safe practices developed and used by various agencies of the U.S. Government, such as venting of propellants and pressurants in spent stages left on-orbit to preclude explosions, separation maneuvers to avoid collisions and any satellite position management and disposal at end of life, if applicable to prevent collisions in high orbits and the possible generation of long-lived debris.

B. Regulatory and Safety Research and Standards Development

Under Executive Orders 12291 and 12498, proposed Government safety regulations and standards must be subjected to a rigorous test of need, cost vs. benefit and impact. No DOT commercial space safety regulatory action is initiated, therefore, without extensive research and analysis.

DOT has an active research program underway to address a wide range of safety issues involving commercial ranges, launch services and orbital operation, and to improve on methods of evaluating reentry safety for both normal and accidental, as well as natural and possibly controlled, reentry of space objects. Planned research will examine the relative effectiveness and cost/benefit of various proposed debris generation and control options that involve either vehicle design (e.g. litter-free systems) and operational practices (e.g. retro-firing maneuvers at apogee to speed up reentry of spent stages left in orbit).

The products of DOT's safety research will be used to identify the regulatory options and standards that will guide future industry practices. Congress has approved funding for DOT's FY 1989 plans to begin developing standards that can be applied to commercial operations in space.

C. Financial Responsibility and Insurance Requirements

DOT has the authority to require that safety measures be implemented by means of insurance requirements or other evidence of financial responsibility. Whereas the purpose of safety standards is to reduce the incidence of accidents, insurance is a mechanism designed to compensate for the consequences of accidents and to protect against the "cost" hazards of orbital debris. DOT expects to issue a rule in the near future which addresses financial responbsibility and allocation of risk, and establishes the basic mechanisms whereby companies may be required to carry insurance. In the meantime, such requirements continue to be imposed on a case-by-case basis pending issuance of the rule.

III. REGULATORY RESTRAINT

The National Space Policy expresses a sensitivity to the potential impacts of orbital debris measures on the commercial sector, stating that such measures must be "consistent with mission requirements and cost effectiveness," and must not unnecessarily prejudice the development and international competitiveness of the U.S. commercial space industry. These same principles are, however, even more forcefully articulated in other Federal regulatory policy statements imposing more stringent standards on regulatory authorities to exercise restraint in their activities.

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Most of the proposed debris reduction solutions add to the cost of the launch process or payload operation. A requirement to deorbit upper stages, for instance, entails weight and performance changes that increase launch costs. In determining what steps the U.S. Government should take to address the orbital debris problem, therefore, it is necessary to consider the economic impact of commercial regulations on the domestic launch industry. Unlike the two governmental sectors (civilian and defense), the private, non-governmental sector functions in a highly competitive environment. The cost of orbital debris measures are passed on to the customer. If the same launch requirements are not imposed on foreign competitors in the launch industry, the U.S. launch firms may have to operate at a distinct competitive disadvantage. Similarly, added costs can have a direct bearing on the competitiveness of space-based technologies (such as satellite communications) as compared to terrestrial alternatives (such as fiber optics communications).

A robust and economically viable commercial launch sector is a necessary component of the National Space Policy strategy to assure the continuance of U.S. leadership in space. Consistent with this objective, DOT's mission under the Act is to promote and encourage a commercial launch industry. While the Act authorizes regulation of the industry as well, DOT's regulatory authority is limited to the extent necessary to ensure compliance with U.S. international obligations and to protect the public health and safety, safety of property and U.S. national security and foreign policy interests. This approach reflects the underlying principles of Federal regulatory policy generally, which provide that regulatory action may not be undertaken unless benefits to society outweigh the costs.

PART FOUR: FINDINGS AND RECOMMENDATIONS

The success of space endeavors depends upon a space environment sufficiently free of debris to enable the safe and dependable operation of spacecraft. An environment overly cluttered with debris would threaten the ability to utilize space for a wide variety of scientific, technological, military and commercial purposes.

In recognition of this potential problem, the Administration's National Space Policy states that:

> "...all space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness."

This section outlines the essential findings of the interagency study on the orbital debris problem and recommends actions to be taken in response to these findings.

I. FINDINGS

A. Limitations on debris measurements and the consequent limitations in debris environment modeling create uncertainty as to the urgency for action and the effectiveness of any particular mitigation measure. The need for enhanced measurement capability has been universally recognized.

B. Left unchecked, the growth of debris could substantially threaten the safe and reliable operation of manned and unmanned spacecraft in the next century.

C. Two different critical areas have been identified for the near term: the low earth orbit environment requires urgent attention because of the high relative velocities among objects in orbit and the large masses in LEO, while the geosynchronous arc requires attention because so many additional spacecraft will approach the end of their maneuver capability within the next few years.

D. Several promising R&D efforts are already underway in various agencies. However, the scope and pace of current R&D plans and activities may not be sufficient to offer future program managers an adequate array of cost-effective technologies and procedures for debris minimization and spacecraft survivability. Insufficient coordination currently takes place between federal agencies pursuing these projects, as well as between government and the private sector.

E. Responsibility for addressing the orbital debris problem cuts across agency boundaries. Currently, there is no single interagency focus for establishing direction, coordinating efforts and overseeing implementation of debris mitigation policies.

F. For various reasons, agencies with operational and regulatory responsibilities for spacecraft have not as yet decided to promulgate policies pertaining to mitigation of orbital debris.

G. The orbital debris problem has both governmental and commercial dimensions.

H. The causes and consequences of orbital debris are global in scope. The scope will continue to widen as more nations become "users" of space or develop their own space programs. While individual nations can take positive steps to alleviate the problem, international cooperation is essential to a satisfactory solution, and some multilateral discussions have already taken place.

I. No comprehensive U.S. Government strategy exists for addressing the debris problem over the long term due to uncertainty about the debris population, the differences in the space systems operated or regulated by the various agencies and the consequent variations in susceptibility to the debris hazard. The need for additional policy and a strategy is recognized.

II. RECOMMENDATIONS

A. Minimizing orbital debris should be a design consideration for all future commercial, civil and military launch vehicles, upper stages, satellites, space tests and missions.

B. Each agency with operational or regulatory responsibilities for spacecraft should develop and distribute internal policy guidance consistent with National Space Policy regarding debris minimization.

C. Current agency operational practices for debris mitigation during launch and space operations should be continued and, where feasible and cost-effective, improved.

D. The following activities should be emphasized and, where appropriate, accelerated:

- efforts to improve debris characterization measurements and inventory through use of ground-based radars and development of a hybrid data base that will provide for rapid information retrieval and database growth

- modeling and statistical analyses of the debris characterization measurements

- analysis of physical evidence returned from space

- technological research directed toward improved shielding and a better understanding of the collision/fragmentation processes

- licensing agency development of performance requirements and regulations to guide private industry activities

- on-going studies of design and operations techniques to minimize the cost of debris elimination.

E. NASA and DoD should undertake a joint study to develop a comprehensive R&D plan to improve the performance of monitoring, modeling and data management capabilities. The plan should define the desired level of confidence in debris characterization data for all of LEO for particles 0.1 cm to 10 cm diameter and the desired deadline for achieving this confidence level. The objective is to achieve the highest feasible level of confidence, taking into account mission requirements and cost-effectiveness. This plan should be provided to agency management for use in preparing agency budget submissions [[within established procedures and schedules.]] The NASA-DoD team should brief the appropriate interagency group on this plan no later than January 1, 1990. This briefing would include a description of the tasks to be accomplished, the priority of each task, necessary funding and an incremental milestone schedule. This briefing would further recommend specific agencies/organizations to be assigned missions for the accomplishment of each designated task.

F. NASA and DoD, in consultation with DOT and the private sector, should undertake a joint study to develop a basic research plan for developing generic technologies and procedures for debris minimization and spacecraft survivability. The plan should build on current research efforts and should indicate a logical research sequence that can be tailored, as necessary, to accommodate various resource levels. This plan should be provided to agency management for use in preparing agency budget submissions [[within established procedures and schedules.]] A NASA-DoD team should brief the interagency group on this plan not later than January 1, 1990. The briefing will include a description of tasks to be accomplished, the priority of each task, funding availability and needs and projected task completion dates. This briefing would further recommend specific agencies/organizations to be assigned missions for the accomplishment of each designated task.

G. An interagency team should study and, as appropriate, develop a plan for debris mitigation in geosynchronous orbits. The study should include an examination of the feasibility of spacecraft disposal options. Consultations with interested private sector parties will be an integral part of this process. The team should brief the interagency group on this plan not later than January 1, 1990.

H. Because the orbital debris problem has important commercial dimensions, solutions will require a continuing dialog between the federal government and the private sector.

I. Representatives of commercial licensing agencies (DOT, DOC and FCC) should continue their discussions to define the boundaries of regulatory authority among the licensing agencies over commercial activities that may produce orbital debris.

J. An ad-hoc interagency working group on orbital debris, chaired by NASA and DoD, should be retained as a coordinating mechanism for issues, policies and activities concerning the orbital debris problem. The working group should report to SIG(Space) or its successor and should make recommendations as appropriate.

K. The U.S. should inform other space-faring nations about the conclusions of this report and seek to evaluate the level of understanding and concern of other nations and relevant international organizations about orbital debris issues. Where appropriate, the U.S. should enter into discussions with other nations to coordinate debris minimization policies and practices.

L. [[The National Space Council should make orbital debris an item for early attention. The Council should review these recommendations and should monitor and coordinate agency implementation of them. The Council should also coordinate interagency deliberations for developing the long-term strategy required to guide government activities and regulations for mitigating orbital debris.]]

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THE ORBITAL DEBRIS PROGRAM PROCESS

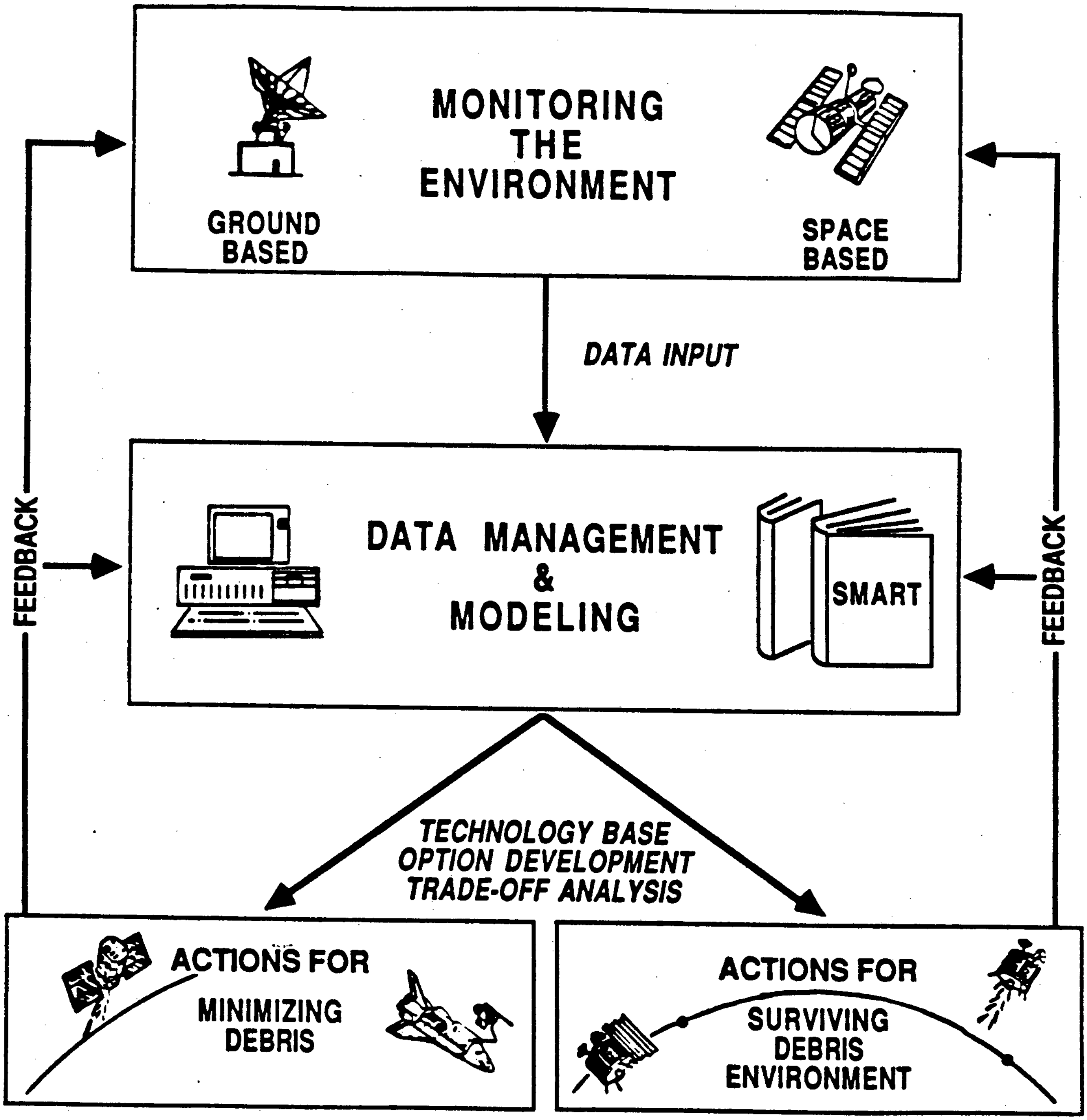

Figure 13: The Orbital Debris Program Process

APPENDIX 1

ON-ORBIT FRAGMENTATIONS

APPENDIX 1
ON-ORBIT FRAGMENTATIONS

Satellite Breakup Status as of 20 July 1988
(Listed by date of event)

Int'l Designator	Common Name	Catalog Number	Launch Date	Event Date	Cataloged	In Orbit	Prob. Cause
1961-Omicron	Transit 4A	119	29Jun61	29Jun61	292	227	Unknown
1962 B Iota	Sputnik 29	443	24Oct62	29Oct62	24	0	Exp. Unintentional
1963-014	Westford Needles	574	09May63	09May63	131	74	Deliberate
1963-047	Atlas Centaur 2	694	27Nov63	27Nov63	19	16	Unknown
1964-070	Cosmos 50	919	28Oct64	05Nov63	97	0	Exp. Intentional
1965-012	Cosmos 57	1093	22Feb65	22Feb65	168	0	Unknown
1965-020	Cosmos 61-63	1270	15Mar65	15Mar65	150	26	Unknown
1965-082	Titan 3C-4	1640	15Oct65	15Oct65	470	93	Exp. Unintentional
1965-088	Cosmos 95	1706	04Nov65	Mid Nov 65	24	0	Unknown
1966-012	Bluebell 2 (OPS 3031)	2015	15Feb66	15Feb66	40	0	Unknown
1966-046	ATDA	2188	01Jun66	Jun 66	54	0	Unknown
1966-059	A5-203	2289	05Jul66	05Jul66	35	0	Test
1966-088	USSR/UNK.1	2437	17Sep66	17Sep66	53	0	Unknown
1966-101	USSR/UNK.2	2536	02Nov66	02Nov66	41	0	Unknown
1968-091	Cosmos 249	3504	20Oct68	20Oct68	104	63	Test
1968-090	Cosmos 248	3503	19Oct68	01Nov68	5	0	Test
1968-097	Cosmos 252	3530	01Nov68	01Nov68	137	65	Test
1969-029	Meteor 1	3836	26Mar69	28Mar69	38	2	Unknown
1969-064	Intelsat 3F5	4052	26Jul69	26Jul69	27	3	Unknown
1969-082	OPS 7613	4132	30Sep69	04OCT69	268	139	Unknown
1970-025	Nimbus 4	4367	08Apr70	17OCT70	356	303	Unknown
1970-089	Cosmos 374	4594	23Oct70	23Oct70	100	47	Test
1970-091	Cosmos 375	4598	30Oct70	30Oct70	45	34	Test
1971-015	Cosmos 397	4964	25Feb71	25Feb71	112	92	Test
1971-106	Cosmos 462	5646	03Dec71	03Dec71	29	0	Test
1973-017	Salyut 2	6399	03Aor73	03APR73	26	0	Unknown
1973-021	Cosmos 554	6432	19Apr73	06MAy73	197	0	Exp. Intentional
1973-086	NOAA 3	6921	06Nov73	28Dec73	195	179	Exp. Unintentional
1974-074	Cosmos 686	7448	26Sep74	26Sep74	20	0	Unknown
1974-103	Cosmos 699	7587	24Dec74	17Apr75 05Aug75	51	0	Exp. Intentional
1972-058	Landsat 1	6127	23Jul72	22May75	227	88	Exp. Unintentional
1966-056	Pageos 1	2253	24Jul66	12Jul75 20Jan76 Jun78	82	13	Unknown (possible collision)
1974-089	NOAA 4	7532	15Nov74	20AUG75	148	139	Exp. Unintentional

Int'l Designator	Common Name	Catalog Number	Launch Date	Event Date	Cataloged	In Orbit	Prob. Cause
1975-080	Cosmos 758	8191	05Sep75	06Sep75	77	0	Exp. Intentional
1975-102	Cosmos 777	8416	29Oct75	26Jan76	63	0	Exp. Intentional
1975-004	Landsat 2	7616	22Jan75	09Feb76	206	55	Unknown
				19Jun76			
1976-072	Cosmos 844	9046	22Jul76	25Jul76	249	0	Exp. Intentional
1976-126	Cosmos 886	9634	27Dec76	27Dec76	74	64	Test
1976-105	Cosmos 862	9495	22OCt76	15Mar77	14*	12	Unknown
1976-063	Cosmos 838	8932	02Jul76	17May77	41	0	Exp. Intentional
1977-065	GMS (Himawari)	10144	14Jul77	14Jul77	166	97	Exp. Unintentional
1976-067	Cosmos 839	9011	08Jul76	29Sep77	64	63	Unknown
1977-068	Cosmos 931	10150	20Jul77	24Oct77	8*	6	Unknown
1977-121	Cosmos 970	10531	21Dec77	21Dec77	65	64	Test
1976-077	NOAA 5	9063	29Jul76	24Dec77	153	152	Exp. Unintentional
1975-027	GEOS 3	7735	09Apr75	14Mar78	5	4	Unknown
1977-027	Cosmos 903	9911	11Apr77	08Jun78	5*	3	Unknown
1978-083	Cosmos 1030	11015	06Sep78	10Oct78	7*	5	Unknonw
1976-120	Cosmos 880	9601	09Dec76	27Nov78	51	9	Unknown
1977-047	Cosmos 917	10059	16Jun77	30Nov78	4*	2	Unknown
1979-058	Cosmos 1109	11417	27Jun79	Sep79	9*	7	Unknown
1979-077	Cosmos 1124	11509	28Aug78	09Sep79	8*	6	Unknown
1979-033	Cosmos 1094	11333	18Apr79	17Sep79	3	0	Exp. Intentional
1965-027	Snapshot	1314	03Apr65	Late Nov 79	41	41	Unknown
				06Dec80			
				23Aug81			
				19Mar83			
				Late Aug 83			
				Jan85			
1979-104	CAT Rocket	11659	24Dec79	Early 80	2*	0	Unknown
1965-016	GREB-6	1271	09Mar65	20Nov80	10	9	Unknown
1964-026	OPS 4412	801	05Jun64	19Dec80	7	5	Unknown
				02Jul82			
1980-030	Cosmos 1174	11765	18Apr80	18Apr80	47	24	Test
1966-005	OPS 1953	1952	28Jan66	18Apr80	11	9	Unknown
				17Sep80			
				Jul83			
1965-048	Transit 5B-6	1420	24Jun65	22Aug80	11	9	Unknown
				24Aug80			
				Jun81			

Int'l Designator	Common Name	Catalog Number	Launch Date	Event Date	Cataloged	In Orbit	Prob. Cause
1978-026	Landsat 3	10704	05Mar78	27Jan81	204	178	Exp. Unintentional
1981-024	Cosmos 1258	12337	14Mar81	14Mar81	2	0	Test
1967-092	OPS 4947	2965	25Sep67	Late Apr 81	7	7	Unknown
1978-098	Cameo	11081	24Oct78	06May81	3	3	Unknown
1981-031	Cosmos 1261	12376	31Mar81	12May81	7*	5	Unknown
1980-057	Cosmos 1191	11871	02Jul80	14May81	5*	3	Unknown
1966-024	OPS 1117	2119	26Mar66	05Jul81	6	3	Unknown
1980-021	Cosmos 1167	11729	14May80	15Jul81	13	0	Exp. Intentional
1981-053	Cosmos 1275	12504	04Jun81	24Jul81	299	292	Unknown
1981-088	Cosmos 1305	12818	11Sep81	11Sep81	8*	4	Exp. Unintentional
1981-016	Cosmos 1247	12303	19Feb81	20Oct81	8*	5	Unknown
1981-071	Cosmos 1285	12627	04Aug81	21Nov81	6*	4	Unknown
1981-028	Cosmos 1260	12364	20Mar81	08May82 10Aug82	69	26	Exp. Intentional
1980-089	Cosmos 1220	12054	04Nov80	20Jun82 25Aug82	79	32	Exp. Intentional
1981-089	Cosmos 1306	12828 13369	14Sep81	12Jul82 18Sep82	9	2	Exp. Intentional
1981-072	Cosmos 1286	12631	04Aug81	29Sep82	3	0	Exp. Intentional
1982-115	Cosmos 1423	13685	08Dec82	08Dec82 09Dec82	31	1	Exp. Unintentional
1983-070	Cosmos 1481	14182	08Jul83	09Jul83	5	3	Unknown
1978-064	Seasat 1	10967	27Jun78	18Jul83 25Feb85	6	2	Unknown
1982-038	Cosmos 1355	13150	29Apr83	12Aug83	30	1	Exp. Intentional
1983-038	Cosmos 1456	14034	25Apr83	12Aug83	10*	5	Unknown
1982-088	Cosmos 1405	13508	04Sep82	20Dec83	33	16	Exp. Intentional
1981-108	Cosmos 1317	12933	31Oct81	25-28Jan84	7*	5	Unknown
1984-011	Westar 6	14688	03Feb84	03Feb84	23	13	Exp. Unintentional
1983-020	Astron Platform	13902	23Mar83	03Sep84	3	1	Unknown
1983-044	Cosmos 1461	14064	07May83	11May85	153	130	Exp. Unintentional
1985-039	Cosmos 1654	15734	23May85	21Jun85	19	10	Exp. Intentional
1979-017	Solwind	11278	24Feb79	13Sep85	287	117	Test
1982-055	Cosmos 1375	13259	06Jun82	21Oct85	58	58	unknown
1985-094	Cosmos 1691	16139	09Oct85	22Nov85	20	20	Unknown
1983-022	NOAA 8	13923	28Mar83	30Dec85	9	4	Exp. Unintentional
1981-058	Cosmos 1278	12547	19Jun81	Early Dec 86	5*	3	Unknown
1984-083	Cosmos 1588	15167	07Aug84	11Aug86	46	1	Exp. Intentional
1986-069	USA 19 USA 19 R/B	16937/ 16938	05Sep86	05Sep86	5	0	Test

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Int'l Designator	Common Name	Catalog Number	Launch Date	Event Date	Cataloged	In Orbit	Prob. Cause
1965-073	Cosmos 86	1584	18Sep65	18Sep65	11	11	Unknown
1967-011	Diademe 1	2674	08Feb67	03Feb67	15	4	Unknown
1967-086	Cosmos 176	2942	12Sep67	12Sep67	12	0	Unknown
1968-025	Apollo 6	3170	05Apr80	13Apr68	17	0	Unknown
1968-117	Cosmos 261	3624	19Dec68	22Dec68	24	0	Unknown
1969-021	Cosmos 269	3775	05Mar69	05Mar69	23	0	Unknown
1970-005	Cosmos 320	4301	16Jan70	16Jan70	7	0	Unknown
1971-041	Cosmos 411	5210	07May71	07May71	9	9	Unknown
1967-001	Intelsat 2 F-2	2640	11jan67	71	37	21	Unknown
1972-078	Cosmos 523	6222	02Oct72	06Oct72	12	0	Unknown
1973-027	Skylab 1	6633	14MAY73	14May73	14	0	Unknown
1973-075	Cosmos 601	6876	16Oct73	06Oct73	14	0	Unknown
1976-012	Cosmos 801	8658	05Feb76	05Feb76	17	0	Unknown
1976-124	Cosmos 885	9615	17Dec76	13Apr77	19	0	Unknown
1977-042	Cosmos 913	10028	30May77	06Sep77	22	0	Unknown
1977-097	Salyut 6	10382	29Sep77	29Oct78	106	0	Unknown
				21Apr79			
				01Jul79			
1979-063	Cosmos 1112	11443	06Jul79	06Jul79	26	0	Unknown
1981-093	PRC 09	12845	19Sep81	02 Oct81	10	0	Unknown
1985-121	Cosmos 1714	16437	28Dec85	28Dec85	7	4	Unknown
1986-024	Cosmos 1736	16647	21Mar86	21Jun86	30	2	Unknown
1986-101	Cosmos 1809	17241	18Dec86	18Dec86	11	11	Unknown
				19Dec86			

Int'l Designator	Common Name	Catalog Number	Launch Date	Event Date	Cataloged	In Orbit	Prob. Cause
1986-059	Cosmos 1769	16895	04Aug86	21Sep86	5	0	Unknown
1986-019	Spot-1 Viking R/B	16615	22Feb86	13Nov86	475	443	Exp. Unintentional
1985-082	Cosmos 1682	16054	19Sep85	18Dec86	24	1	Exp. Intentional
1987-004	Cosmos 1813	17292	15Jan87	29Jan87	194	49	Exp. Intentional
1971-003	Meteor 1-7 r/b	4849	20Jan71	Jun87	3	3	Unknown
1987-059	Cosmos 1866	18184	09Jul87	26Jul87	11	0	Exp. Intentional
1987-078	Aussat k-3/ECS-4	18352	16Sep87	16-19Sep87	5	5	Unknown
1986-059	Cosmos 1769	16895	04Aug86	21Sep87	6	0	Unknown
1978-096	Tiros N	11060	13Oct78	28Sep87 04Oct87	5	0	Unknown
1985-030	Cosmos 1646	15633	18Apr85	20Nov87	25	2	Unknown
1987-020	Cosmos 1823	17535	20Feb87	17Dec87	68	68	Unknown
1985-042	Cosmos 1566 deb.	15773	30May85	05Jan88	11	9	Unknown
1987-108	Cosmos 1906	18713	26Dec87	31Jan88	38	0	Unknown
1988-007	Cosmos 1916	18823	03Feb88	27Feb88	2	0	Unknown
1978-100	Cosmos 1045 r/b	11087	25Oct78	09May88	29	29	Unknown

*Note: Fragments in highly elliptical, "deep-space" orbits are extremely difficult to track. Consequently, the number of pieces of debris cataloged with these orbits is very small and probably not representative of the true population.

APPENDIX 2

APPROACHES TO OTHER GOVERNMENTS

This appendix is classified and has been provided under separate cover.

APPENDIX 3

PRIVATE SECTOR INPUT

APPENDIX 3

PRIVATE SECTOR INPUT

I. Request for Private Sector Input:

In August 1988 an announcement was placed in the Commerce Business Daily requesting private sector input and comments about orbital debris issues.

II. Response :

The companies and organizations which responded are listed below, in alphabetical order:

Applied Research Corporation
Astro Innovations, Inc.
Committee To Bridge The Gap
EOSat
General Research Corporation
Grumman Space Systems
Kaman Sciences Corporation
KMS Fusion Corporation
Teledyne Brown Engineering

III. Summary of Responses:

Applied Research Corporation

Proposes a simple, relatively low cost space experiment to obtain real debris data over a two to three year period. These data, together with a good analytical model could accurately predict and then be used for space damage assessment.

Astro Innovations Inc.

Advocates change to international laws that would allow and encourage active salvage operations at geosynchronous and GTO altitudes. The sovereign rights of space-faring nations could be maintained, while affording commercially attractive salvage opportunities to those so able.

Committee To Bridge The Gap

Proposes a ban on the use of nuclear power supplies in Earth orbit.

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General Research Corporation

Describes two Orbital Debris Mitigation Systems conceptually designed to be used in a variety of configurations to solve a number of debris-related problems. The first system is a maneuverable free-flying spacecraft, and the second is a shielding unit, or units, attached to the space system being protected. General comments about potential applications, benefits, and developmental costs are provided.

Grumman Space Systems

Proposes the use of their Tumbling Satellite Retrieval Kit to capture large pieces of orbital debris.

Kaman Sciences Corporation

Proposes a laser device that could be used to slow and deorbit a variety of orbital debris. Existing devices, experiments, and analyses (esp. DoD) will permit rapid validation of this concept.

KMS Fusion Corporation

Stated interest in attending Orbital Debris discussions. They saw their involvement in the Cosmic Dust Collection Facility and a proposed Debris Collision Warning System as potentially useful.

EOSat

As operator of Landsat, EOSAT supports government action and international cooperation to deal with the growing problem of orbital debris.

Copies of the full reports mentioned in the responses were reviewed by members of the IG (Space) Orbital Debris Working Group and are available at NASA Headquarters.

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